Final Report

6217 – Carnsew Pool Tide Mill Restoration

For

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This report does not constitute an engineering design or complete installation plan, and as such, it is not intended for construction purposes. Furthermore, any discussions within this document of marine operations are intended as a guideline: potential installation contractors shall develop their own means and methods of installation.

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1 Executive Summary

Tidal range energy can be harnessed by constructing barrages across estuaries, and using turbines to generate electricity with the rise and fall of the tides. Hayle Harbour has two potential tide pools – Carnsew and Copperhouse – that could be used to generate *tidal range* power. Two complications are that: first, Carnsew Pool is intended for sluicing operations to improve the navigable depth of the Hayle Harbour estuary channel; second, Copperhouse Pool is used by the Environment Agency for Hayle flood protection. The levels of energy available are akin to micro and mini-hydro range (50KW to 1MW), lower than large *tidal range* schemes, such as Swansea Lagoon at 320MW installed capacity. There are no technologies on or close to market available at the right scale for such schemes.

In the absence of existing technological solutions, this analysis uses: first, an off-the-shelf 'very low-head' river hydro turbine to investigate civil engineering feasibility of the Carnsew and Copperhouse options; second, a theoretically scaled *tidal range* turbine to investigate economic feasibility:

- Civil Engineering Feasibility – the analysis shows that there are practical and affordable civil engineering solutions to install *tidal range* turbines in 3 identified locations in the 2 pools. A modular installation process, using precast concrete modular installation pods, will be cost-effective and portable to other mini and micro-tidal range schemes;
- Economic Feasibility – the analysis shows that the schemes would be economically feasible, with *levelised costs of energy* potentially below £100MWH^{-1}, well below the Swansea Lagoon strike price bid of £168MWH^{-1}. A theoretical installation of 4 x 30KW bulb turbines would deliver annualised power of 474 MWH, with an LCOE of £98MWH^{-1}, sufficient to power around 146 homes. If the civil engineering costs can be reduced, then LCOE's below £86MWH^{-1} could be in achieved.

The key qualification is that technical and economic feasibility relies upon the design and development of small scale *tidal range* turbines, with operational characteristics akin to large scale tidal range turbines and cost and operations & maintenance characteristics akin to low head hydro river turbines. If developed, the turbines and modular installation methodology would be portable, to: other Cornish sites; further afield throughout UK; and internationally.

The schemes would give rise to a number of environmental and socio-economic impacts:

- Environmental – the scheme(s) would lead to relatively low annual reductions in the intertidal zone, but the impact on wading birds would need to be examined over a lunar cycle. The impact on marine flora and fauna is likely to be very low indeed;
- Societal – the scheme(s) will have some impact upon existing plans to sluice the harbour, but the net impact may be low. This is because although there will be some loss in ebb-tide sluicing impact, this may be counter-balanced by reduction in the dominance of the flood-tide silting mechanism, as a result of the scheme(s) operation;
- Economic – the scheme(s) could deliver significant net-economic benefits. For Hayle, the schemes would provide a second marine renewable energy source alongside WaveHub and leverage the Hayle Marine Energy park; for Cornwall and the UK, the redevelopment of the world's first tide mills could secure a technology and export opportunity. The technology is particular apposite to developing countries, and well placed to secure DFID funding.

The scheme(s) would likely best be introduced as part of a more comprehensive integrated approach, that optimizes all sluicing and flood protection with renewable energy generation. This would need to be the subject of an in-depth pre-front end engineering design process.

Pending such study, the key conclusion is that, when viewed from a marine renewable energy perspective, the scheme(s) are technically and economically viable, and worthy of analysis in detail.

2 Introduction

There has been no restoration of an historic tide mill anywhere in the world, but some preliminary feasibility work has been conducted on the Carnsew Pool at Hayle, one of Cornwall's former tide mills. This work, together with Cornwall's specialisms in tidal energy and government/public support for low environmental impact predictable renewable energy, provide a world-first opportunity to restore an historic tide mill, thus delivering tidal energy at micro or mini scale[1] for the first time in UK, immediately adjacent to both WaveHub and to Cornwall's Marine Energy Business Park. Drawing on WRAP funding, Community Energy Plus (CEP) are working with Mojo Maritime Limited (Mojo) to establish the high level feasibility of converting Carnsew Pool into a tide mill. This report sets out findings of the feasibility analysis.

The purpose of the report is to examine the technical and economic feasibility of installing tidal range power generation technologies in the Hayle Harbour, draw conclusions, and make recommendations.

The report is structured into 6 overarching sections. First, a non-technical overview of the science and technical background to *tidal range* energy generation, using both existing and historic technologies and the technical and economic contest of the Hayle Harbour location are provided. Second, the modern technology options relevant to the Hayle site, such as exist, are reviewed. Third, 3 sites for tidal turbine deployment are examined, and a conceptual analysis of how such turbines would be installed from a civil engineering and operational perspective, presented. Fourth, the economic feasibility of tidal range power generation is examined, using Levelised Cost of Energy (LCOE) modelling. Fifth, the environmental, societal and economic impacts are considered, from an oceanographic and technical perspective. Sixth and finally, conclusions and recommendations are made.

3 Background

3.1 Tidal Range Energy

Tides are caused by a number of complex gravitational and oceanographic factors, but simplistically the two key drivers are the position of the sun and moon and, thus, the gravitational effect both have on the oceans and coastal seas. When the moon's and sun's gravitational forces act in unison, then the overall tidal effect is higher, which delivers the Spring tides. When the forces are in opposition, then the tides are lower, which delivers the Neap tides. *Tidal range* is the marine term to describe the height between high tide and low tide, usually described in metres. A mariner's rule of thumb is that the tidal range for a Neap tide will be about half the range of a Spring tide.

Tidal energy is one of the last great untapped renewable energy resources. Two key advantages of tidal energy are that: first, it is completely predictable; second, it has high 'power density', that is the extractable energy per unit area is high. Tidal energy can be harvested in two ways. *Tidal stream* energy uses technologies akin to underwater wind turbines to extract kinetic energy from high speed tidal streams, such as those in the Pentland Firth and Channel Islands. *Tidal range* energy uses technologies akin to hydroelectric dams to extract potential energy from the change in water levels in

[1] Drawing on the International Renewable Energy Authority Associations hydropower classifications (large – greater than 100MW; medium – 20MW-100MW; small – 1MW-20MW; mini-100KW-1MW; micro – 5KW-100KW), this report uses the terms mini and micro tidal range to cover the 5KW to 1MW range. *Hydropower, Volume 1: Power Sector, Issue 3/5*, dated June 2012, International Renewable Energy Agency, p.11.

inshore and estuarine locations, by constructing barrages to enclose water masses. The difference in

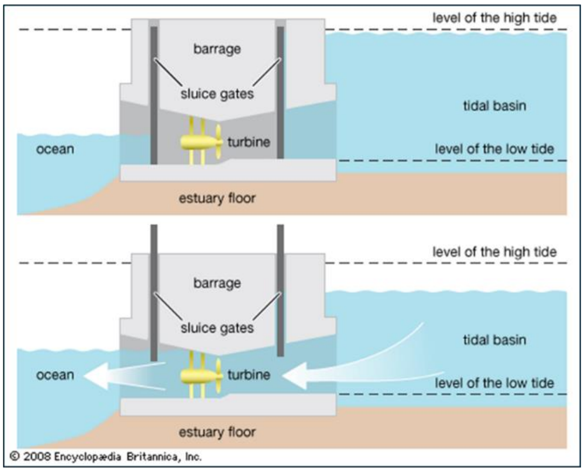

Figure 1: Tidal Range Energy Extraction

water levels on either side of the barrage is used to drive turbines in the dams to generate electricity, as shown in Figure 1. **The power available from a *tidal range* scheme is determined by two mathematical factors: the wetted salt water *area* enclosed by the barrage; the square of the *tidal range*.**[2]

The world's longest standing *tidal range* scheme is the La Rance Barrier, which has been in operation since the 1960s. La Rance has an installed capacity of 240MW.

Figure 2: La Rance Barrier

Recently refurbished and power optimised, there are no plans to decommission the La Rance in the foreseeable future, notwithstanding that it has already been in operation for over 45 years.

More modern schemes have been installed in Korea, at Sihwa; and are under consideration in Swansea Lagoon. What characterises all modern tidal range barriers is that they are medium or large-scale tidal range schemes, built at grid-utility scale, and inevitably requiring very high capital expenditure (CAPEX). Similarly, the technologies installed are large and expensive – each of the Swansea Lagoon turbines will be around 7m in diameter, with a rated power of 16MW.

2 It thus follows that, because Spring tides are roughly twice the height of Neap tides, the power available will be 4 greater in Springs.

3.2 Tide Mills

Tidal range energy does, though, has a long lineage dating back to 60AD in the British Islands, when it was used to drive water wheels in tide mills, for a range of agricultural and other milling purposes. The tide mills operated in exactly the same way as modern tidal range schemes, by enclosing an estuarine body of water with a barrage, and taking power on the ebb-tide through the use of horizontal or vertical axis mill wheels.

Figure 3: Historic Tide Mill

During the height of the tide mill period, Cornwall and Devon were home to over 30 tide mills, but all fell into disrepair in the late 19th and early 20th Century, replaced by fossil fuel power sources. Many if not most of these sites are, in principle, capable of refurbishment.

4 Hayle Overview

4.1 Hayle Harbour & Estuary

Of the 20 or so potential Cornish tide mill refurbishment sites, Carnsew and Copperhouse Pool have specific attractions because: the Hayle Harbour site is sheltered, and low risk from a civil engineering perspective; the enclosed water masses are quite large, for tide mills, and offer reasonable power potential; the existing infrastructure appears sound; grid connection is close; there are political and local economic advantages in the sites' location, adjacent both to WaveHub and the Cornish Marine Energy Business Park.

The Carnsew and Copperhouse Pools lie on a SW-to-NE orientation, sat either side of, and discharging into, Hayle Harbour. There are 3 potential sites for tidal range turbines: Carnsew Sluice Culverts; Carnsew Sluice Gates; Copperhouse Flood Gates; all 3 located as shown in Figure 2.

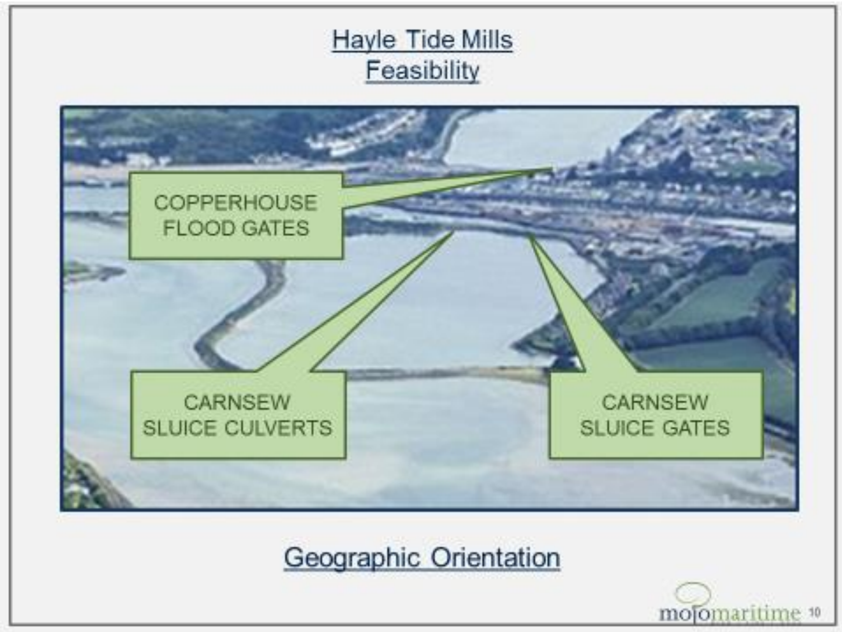

Figure 4: Hayle Harbour & Tide Pools

Carnsew and Copperhouse both have large intertidal areas: Carnsew's is around 148,252 m^2; Copperhouse's is around 248,328m^2; both are positive factors in potential yield(s). Against this, both pools are relatively shallow, with low effective tidal ranges compared to other sites, which is a negative factor in potential yield(s).

5 Feasibility Analysis

5.1 Analytic Strategy

The complication in a feasibility report of this nature is that **there are no commercially-off-the-shelf (COTS) technologies on the market, in R&D or at concept stage, for generating tidal range energy at micro or mini scale as defined in this report.**

The consequent challenge is two-fold. First, to establish the civil engineering feasibility of installing technologies that do not exist. Second, to establish key input data – in particular yields, CAPEX for both the turbines and civil engineering, and operational expenditures (OPEX) – for technologies that do not exist. A third site-specific challenge is the need to gain insights into the potential requirement to use Carnsew Pool for sluicing purposes.

A literature review (see Annex A) was conducted, but essentially revealed only contextual information. Critically, the two references[3] that investigated tidal energy installations at Hayle used *tidal stream* mathematics and technologies, which, as discussed later, are much less efficient than *tidal range* technologies in inshore schemes of this nature. These were thus of limited use for either the technical or economic feasibility assessment.

For all of these reasons, a pragmatic approach has been adopted:

3 Rubicon Marine Ltd & Western Hydro Ltd, *Conceptual Feasibility Study for the Replacement of Derelict Sluice Gates at Carnsew Pool, Hayle, with a Tidal Current Turbine Array*, February 2006; University of Plymouth, *Harnessing the Power of the Tide: A Tidal Scheme Proposal for Carnsew Pool, Hayle*, dated January 2007.

- first, a technology review is conducted on, first, large scale *tidal range* technologies and, second, on the '*very low head hydro'* power generation in hydro-electric scheme; with a particular focus on scaling down the former and marinising[4] the latter;
- second, a modern COTS low-head hydro technology is selected to undertake the installation and civil engineering feasibility analysis;
- third, a theoretical scaled tidal range turbine is selected to undertake the resource and LCOE analysis, taking account of the known price points, for economic feasibility modelling;
- fourth, the physical oceanographic impacts of the theoretical installation are examined using coastal modelling, to provide insights into potential environmental and societal impacts;
- fifth and finally, the analysis is drawn together in a narrative discussion, with conclusions and recommendations.

The technical focus of the report is on civil engineering feasibility and on establishing economic feasibility using quantitative resource analysis to establish Levelised Cost of Energy (LCOE) of the 3 potential Hayle tidal range scheme(s).

5.2 Levelised Cost of Energy

LCOE is the energy standard term used to describe the unitised cost, through life, of delivering energy from a particular project, be it fossil fuel, nuclear or renewables; and is defined as:

> *'The Levelised Cost of Energy generation is the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in £/MWH.*
>
> *The Levelised cost of a particular generation technology is the ratio of the total costs of a generic plant (including both capital and operating costs), to the total amount of electricity to be generated over the plant's lifetime. Both are expressed in net present value terms. This means that future costs and outputs are discounted, when compared to costs and outputs today.*
>
> *This is sometimes called a life cycle cost, which emphasizes the "cradle to grave" aspect of the definition. The Levelised cost estimates do not consider revenue streams available to generators …*
>
> *As the definition of Levelised costs relates only to those costs accruing to the owner/operator of the generation asset, it does not cover the wider costs that may in part fall to others, such as the full system balancing and network investment, or air quality impacts.'*[5]

In simplistic terms, high level preliminary investment appraisal is undertaken by comparing the calculated LCOE with the 'strike price' offered for the generated electricity, to establish whether the plant owner is able to make an operating profit; if so, then the technology or project is deemed economically feasible.

The LCOE analysis herein is conducted using algorithms developed by sub-contractors, CSB Consilium, for *tidal range* projects and in use now for over 10 years, including on Swansea Lagoon.

5.3 Hayle Harbour – Sluicing & Flood Protection

A key qualitative issue that emerged in the preliminary analysis is the desire to use Carnsew Pool to improve sluicing of the Hayle Estuary, to thus improve the maintenance of depths in the navigable channel.

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4 The terms 'marinising', 'marinised' and 'marinisation' are commonly used offshore as a convenient short-hand for converting onshore technologies for offshore use, and is used in this way in this report.

5 Department of Energy & Climate Change, Electricity Generation Costs 2013, July 2013, p.5.

The Harbour Master has gained agreement from RSPB and Natural England for trial sluicing for 1 day per lunar (i.e. tidal) month. Subject to the trail results, the Harbour Master's preference is for a long-term sluicing operation, for 10 days over the Spring tides of each lunar month. The maximum power outputs of tidal range schemes occur at Spring tides, thus this intention may have a bearing on the overall economic feasibility of the project, if the sluicing interferes with power capture.

For this reason, although not within the study's scope, it has been decided to also investigate options for the installation of tidal range technologies in Copperhouse Pool, which is adjacent to Carnsew Pool, as both an alternative or complement to Carnsew Pool. The tidal flow into Copperhouse Pool is via a flood gate, owned by the Environment Agency (EA), the purpose of which is flood protection, against both tidal storm surges and/or groundwater run-off. The flood protection requirement will thus bear on any Copperhouse tide mill scheme design.

6 Technology Options

The technology review has investigated *tidal stream* and *tidal range* options and, within the latter review, a number of (potential) tidal range technologies. **The key finding is that no technologies exist that are optimized to extract energy from mini and micro-scale tidal range projects.** There are, though, options that have the potential for adaptation and two have been selected as a basis for civil engineering and economic feasibility analysis.

6.1 Tidal Stream

Tidal stream technologies work in a manner akin to offshore wind turbines, harvesting energy from the high energy tidal streams. Figure 5 shows one of the smaller turbines currently on the market, the Tocardo T1, with a nominal installed capacity of 100KW.

Figure 5: Tidal Stream Turbines

The general view in the tidal sector is that tidal stream is economically feasible when tidal stream speeds are 2.0ms^{-1} (circa 4 knots) and above. Whilst there are potential tidal streams of around this speed in the vicinity of the Copperhouse Flood Gates, the smallest of the current tidal stream technologies – the Tocardo T1 and Schottel Instream Turbines – require minimum water depths of 4.0 m or greater, which is greater than the useable depths in Copperhouse, and indeed Carnsew. Furthermore, tidal range technologies provide a more efficient opportunity to extract energy in coastal and inshore locations, because of the higher effective power conversion potential of the turbines[6]. For all of these reasons, tidal stream extraction has been excluded as an option in Hayle.

6.2 Tidal Range

Tidal range is the sea water equivalent of low-head hydro, i.e. hydroelectric generation from sites where there is a low 'head' of water above the hydro-electric turbine. The low head in turn places limitations of the way that power is extracted. Generally speaking, low head technologies rely on reaction rather than impulse power conversion. Reaction machines develop torque by reacting to the weight and lower pressure of water and are lighter and cheaper to manufacture. Whereas impulse machines develop torque from high pressure velocity jets and are heavier and more expensive to manufacture.

6.2.1 Large Scale Tidal Range Technologies

The technology approach adopted for modern tidal range power projects in France, Canada, China and South Korea has been Kaplan bulb turbines. Kaplan bulb turbines are also the intended technology for Swansea Bay Lagoon.

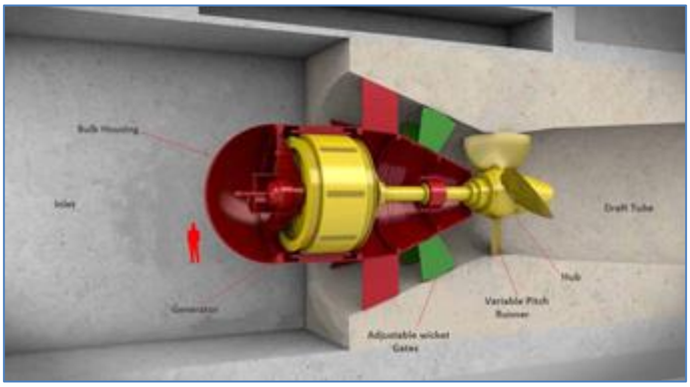

Figure 6: Swansea Bay Lagoon Bulb Turbine

From face-to-face discussions with the Tidal Lagoon Swansea Bay Limited[7], a Kaplan bulb turbine with a 6 mode operation capability is the clear technology winner. 6 mode operation enables the turbine to: generate power on the flood and ebb tides; pump water in both directions; sluice water in both directions. This capacity in turn allows the schemes control systems to maximize energy capture. For example, by pumping water into the lagoon or enclosed water area to increase the head over and above that achieved at high tide, greater yields can be achieved over a tidal cycle.

When in the power generation mode, a bulb turbine operates more efficiently in what is termed the 'direct flow direction', that is with the bulb (rather than the turbine) pointing into the flow (in Figure 5, this is with flow direction from left to right into the turbine); power generation is reduced in the 'reverse flow direction' (in Figure 5, this is with the water flow from right to left).

Bulb turbines with the 20MW rated power planned for Swansea Bay Lagoon are necessarily large, with a turbine diameter of 7.35m and weight of 700 tonnes. They are therefore not feasible for inshore locations, such as Hayle. But there is no technical reason why scaled down versions would not be

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6 Note that the two previous studies of Hayle assumed tidal stream rather than tidal range technologies, with the result that the findings therein would be less economic. See *Carnsew Tidal Turbines Feasibility*, Rubicon, dated February 2006; *Carnsew Tidemill Dissertation*, University of Plymouth, dated 2008

7 Tidal Lagoon Workshop, Bangor University, 17-18 May 2016,

http://tidalenergytoday.com/2016/05/26/bangor-university-hosts-tidal-lagoon-workshop/

feasible. GE-Andritz have already constructed a scale R&D version of the Swansea Bay Lagoon bulb turbines, and operated it successfully under representative scale conditions, for R&D purposes[8].

6.2.2 Low-Head Hydro Technologies

'Low head hydro' is the term used to describe small scale river turbines, usually installed at mini or micro-scale. In theory, there are a number of technological approaches, based around impulse turbines. Historic tide mills have used traditional water wheels and horizontal and vertical impulse wheels akin to Francis turbines; other potential approaches could include Archimedes screws.

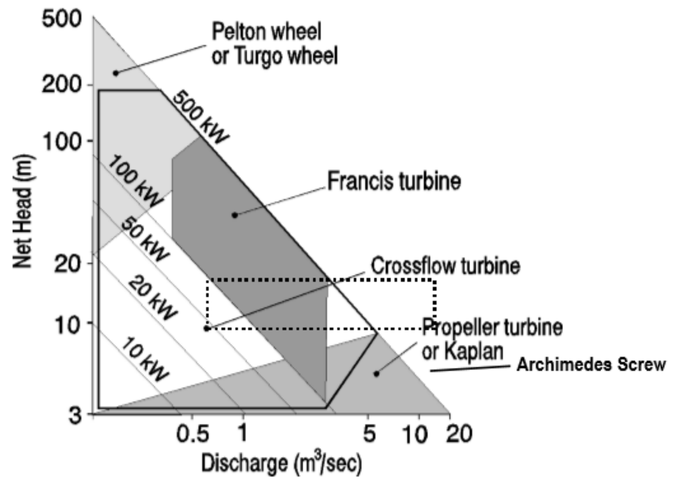

Figure 7: Low Head Hydro Turbine Technologies

But as Figure 6 shows, for *very low head* hydro – i.e. with effective water heads of 5m and below – Kaplan bulb turbines are recommended: exactly the same technology as the large scale tidal schemes, such as La Rance and Swansea Bay Lagoon, but on mini and micro-scale.

6.2.3 Technology Selection

There are no *very low head* river turbines on the market that can be used in mini or micro-*tidal range* schemes. But there are river turbines of Kaplan bulb design at around the right scale, and these thus provide a useful proxy, pending development of mini and micro-scale tidal range turbines, with which to assess civil engineering. Similarly, Kaplan bulb tidal range turbines can be theoretically scaled-down to assess economic feasibility.

6.2.3.1 Civil Engineering Feasibility Technology Selection

Thus, in the absence of any existing technology, the report uses a modern small scale low head hydro bulb turbine, the Voith StreamDiver, as a proxy for a theoretical tidal range turbine. A schematic of StreamDiver is at Figure 8 below.

[8] Tidal Lagoon Workshop, Bangor University, 17-18 May 2016, http://tidalenergytoday.com/2016/05/26/bangor-university-hosts-tidal-lagoon-workshop/

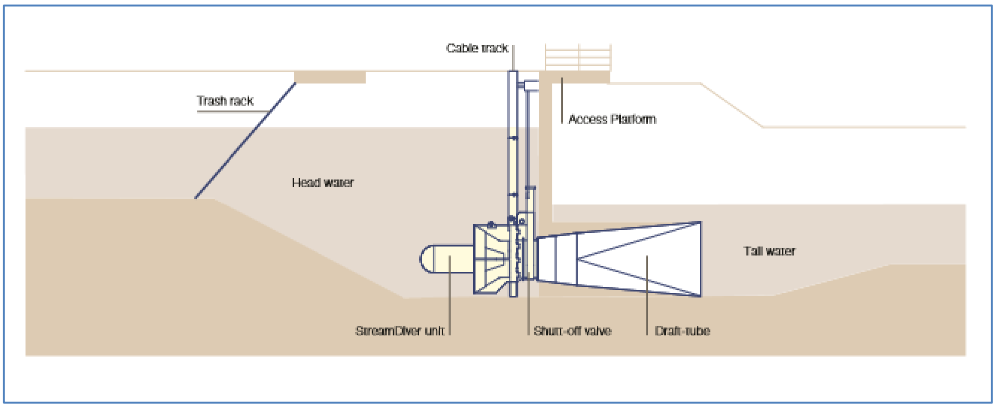

Figure 8: StreamDiver Low Head Hydro Turbine

The smallest StreamDiver unit is 1.38m square and 6.00m in length. It lacks some of the features that would be desirable in an optimized tidal turbine for inshore locations, in particular the 6 mode operation. Notwithstanding these shortfalls, and after exploratory conversations with Voith's engineers, the StreamDiver's dimensions, weights, installation and O&M methods for the civil engineering feasibility analysis.

6.2.3.2 Economic Feasibility Technology Selection

In parallel and again in the absence of a COTS tidal range turbine of the scale appropriate to Hayle, this report uses a theoretically scaled-down version of a Kaplan bulb turbine akin to the La Rance and Swansea Bay Lagoon technologies, to conduct 0D tidal range resource and LCOE analysis. Price and power points are achieved by applying industry standard scale factors, cross-referenced with *very low-head* hydro turbine price and installation data.

7 Civil Engineering Feasibility

7.1 Voith StreamDiver Technology

The Voith StreamDiver is a COTS river turbine, optimized for low head hydro. The unit is designed so that construction costs are minimized, with the power unit installed in the water with only the power cable exposed. The entire drive train, consisting of the turbine, shaft, bearings and generator, is situated in the bulb turbine housing. The bulb is filled with water, which lubricates the bearings and rules out any risk of water contamination. Although the technology is not designed for sea water immersion, the same water lubrication approach has been successfully used in Voith's larger tidal stream turbine, so in principle Voith believe that marinisation of the StreamDiver should be feasible.

Figure 9: StreamDiver River Installation

Standard voltage for the StreamDIver is 400V. The unit is equipped with temperature, vibration and leakage monitors, all connected to a programmable logic control, located in a control cubicle.

The StreamDriver is designed for modular installation. The device weighs less than 10 tonnes, and can be installed or removed using a mobile crane or bespoke lifting gantry. O&M is undertaken by device removal. For the purposes of the civil engineering feasibility analysis, the smallest version of the StreamDiver is used, with a turbine dimension of 1.38m, and overall length of 7.58m.

7.2 Turbine Modular Housing Concept

Because of the potential broader utility of tidal range power generation at mini and micro scale, a modular approach was designed for turbine installation. The concept is a pre-cast concrete shell within which to locate a bulb turbine, of modular design to allow single or multiple turbines to be installed according to the tide mill or tidal range scheme site requirements. Figure 10 shows the StreamDiver units placed with the modular housing; Figure 11 shows the external elements of the housing, including gridded protection of the water inlets and exits.

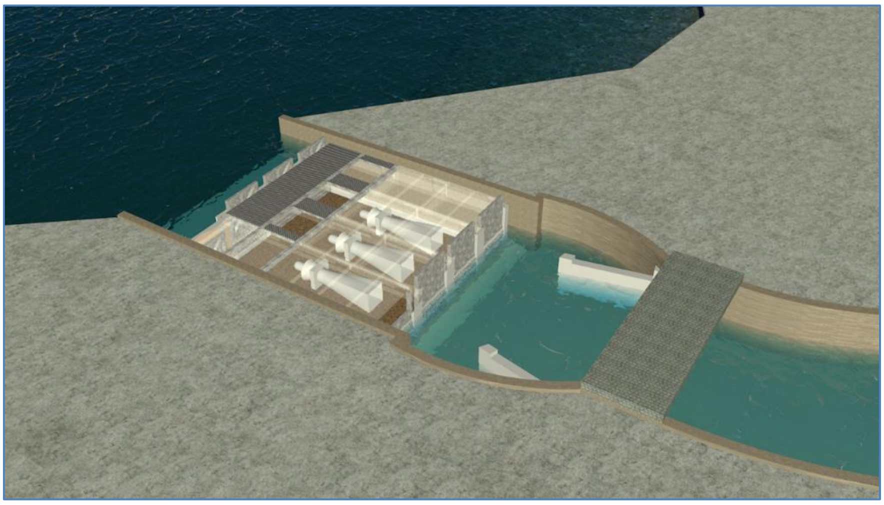

Figure 10: Civil Engineering – Turbine Placement

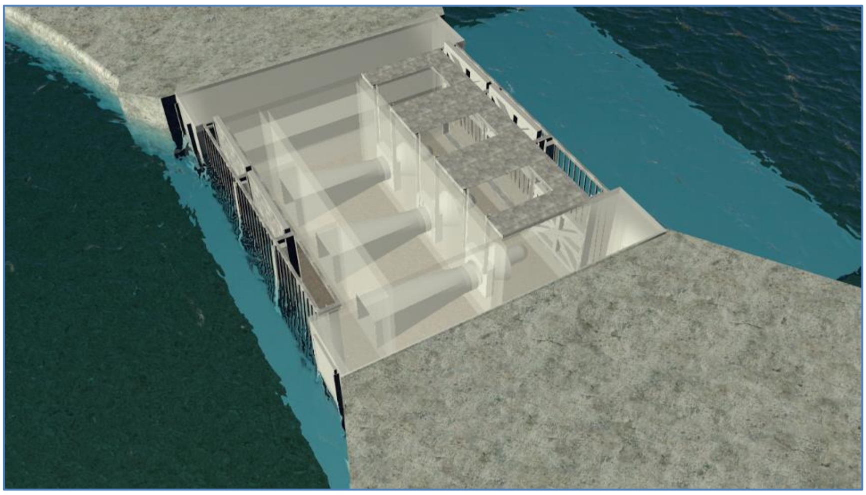

Figure 11: Civil Engineering – Installation Unit Surround

Each modular installation unit comprises a pre-cast open top interlocking concrete housing, sized to suit a generic turbine size. The pre-cast concrete installation unit has interlocking features to allow one or several units to be placed together side-by-side.

The ceiling section of the installation unit, above the turbine head, has a steel structure that incorporates a rail system for a gantry crane. The steel structure would be covered in removable fibreglass grating/steel plating, to enable removal of the turbine bulb unit for O&M purposes. The ceiling section to the rear of the turbine is covered with pre-cast concrete slabs.

At each end of the installation are debris collectors, which can be cleaned manually, or using an automated system, depending the needs of the specific project site.

There is also the possibility of a penstock of steel construction, adjoining the units, to facilitate sluicing or small craft locking, operated either manually or electorally via a control system.

7.3 Turbine Modular Installation Concept

Although each particular installation strategy would be necessarily site-specific, installation would use this generic approach:

- site preparation – the turbine site would be made dry, using coffer-dams, and preparatory groundworks undertaken. Preparatory dredging & civil engineering would also be conducted, as dictated by the specific site requirements;
- transportation – the modular installation units, with turbines pre-installed, would be transported to site, on the back of a standard 40ft articulated vehicle, with no specialist transportation requirements;
- unit installation – the modular units would be craned into place fully assembled, together with the debris collectors (and penstocks if required at the site);
- surrounding construction – with the units seated together, and depending on the overall site width, civils engineering would be undertaken to complete the barraging between the installation units, the penstock, and the existing barrage;
- flooding-up – the coffer-damming would then be removed at this point to allow the units to flood, and the concrete top slabs craned into place to cover the outlet housing unit only. With the units flooded up, the steel grating structures would then be bolted onto the modular housings;
- control and grid connection – the turbines controls and communications would be connected, and the power grid connections made;
- commissioning – a manufacturer's test-and-evaluation process would be undertaken, to confirm that the turbines were operating in accordance with design specifications;
- landscaping – with the commissioning process complete, the pre-cast concrete ceilings would be installed, and the site works completed, with fences erected, and landscaping conducted in accordance with the project plan.

Although each particular installation strategy would be necessarily site-specific, an illustrative timescale for an installation of 3 turbine units and 1 penstock unit would be 7-10 days.

7.4 Carnsew & Copperhouse Specific Site Analyses

This generic approach would be adapted as required for the 3 locations under investigation: Carnsew Culverts; Carnsew Sluice Gates; Copperhouse Flood Gates. These different installations are shown below. For illustrative purposes, it is assumed that the same outfit of 3 StreamDiver turbine units and 1 penstock unit is installed in each of the 3 sites.

7.4.1 Carnsew Sluice Culverts Site

From a civil engineering perspective, Carnsew Culverts site is the most complex. The culverts are understood to date from the early 1940s, and there is evidence of civil engineering wear and tear. There is significant water turbulence in the culverts, particularly where the two Carnsew pool culverts discharge into the 4 Hayle Harbour side culverts. The culverts are also the site of significant mussel growths. The existing location is shown in Figure 12 below.

Figure 12: Carnsew Culvert – Existing Site

The Carnsew Sluice Culverts dimensions are as follows: Carnsew Pool Side – 2 circular culverts, 2.13 m diameter; Hayle Harbour Side – 4 oval culverts at 2.00m high and 1.00 m wide.

Unlike the other sites under consideration, the generic StreamDiver installation would require significant civil engineering preparation, once coffer-dams were in place. A conceptual illustration of the installation is shown at Figure 13 below, as viewed from the Carnsew Pool perspective.

Figure 13: Carnsew Culvert – Pool Perspective

Figure 13 shows the installation with 3 turbine lifting gantries in place for installation, and 1 turbine in the process of being installed. Once the installation is complete, gantries would be removed and the site landscaped along the lies in Figure 14 below.

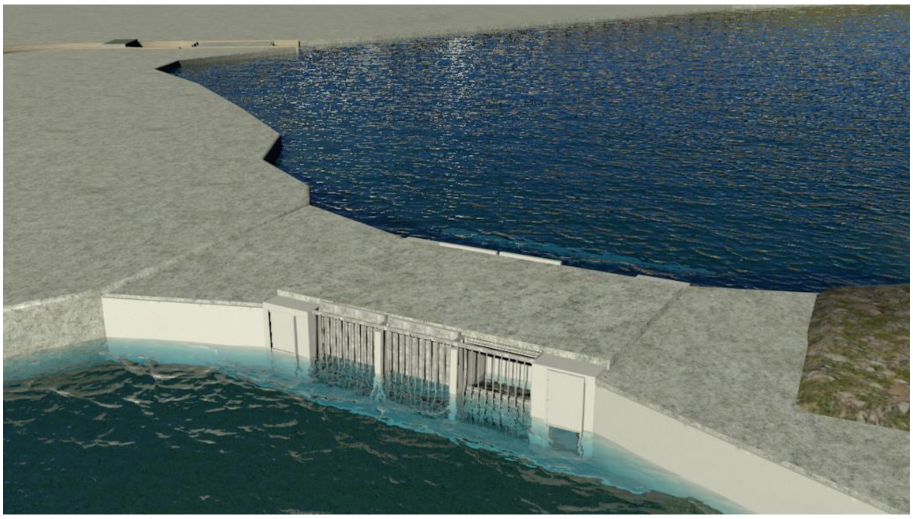

Figure 14: Carnsew Culvert – Pool Perspective

7.4.2 Carnsew Sluice Gates Site

In civil engineering terms, the Carnsew Sluice Gates location is the simplest. The gates and the surrounding civil engineering was installed as part of a restoration of the sluicing capacity in 2014, and thus extremely well found in civil engineering terms. The new lock gates, entrance and exit are shown in Figure 15 below.

Figure 15: Carnsew Sluice Gates – Existing Site

The main dimensions for the Carnsew Sluice Gates site are: Carnsew Pool side channel, of 15.60m wide and 5.84m in height, leading to the sluice gates; Hayle Harbour side, two modern gates, in the sluice channel, which 9.5m wide and 5.84 m in height. A conceptual illustration of the installation is shown at Figure 16 below, viewed from the Carnsew Pool perspective.

Figure 16: Carnsew Sluice Site – Pool Perspective

Figure 16 shows: 1 turbine lifting gantry in place, and 1 turbine being removed for O&M purposes; the sluice penstock open. Again, once the O&M operation was complete, the site would be returned to its operating condition, as shown in Figure 17 below.

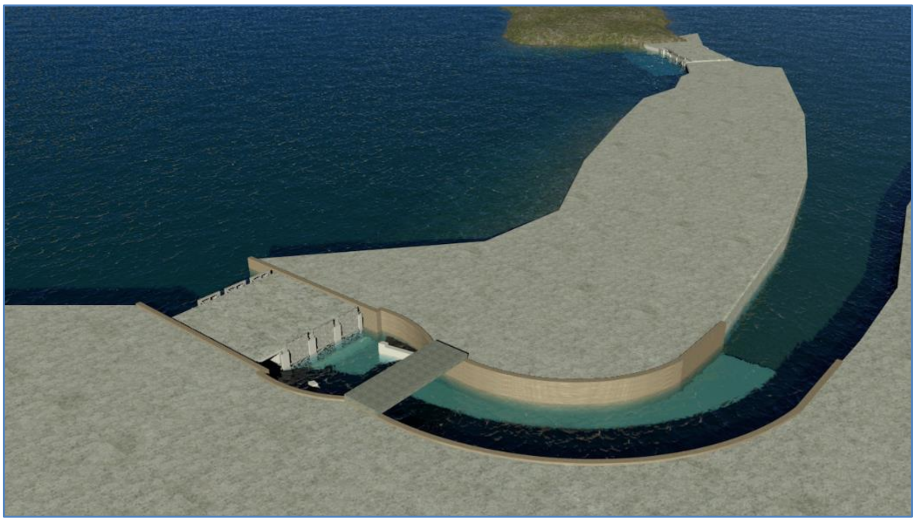

Figure 17: Carnsew Sluice Site – Harbour Perspective

Whilst the scheme installation will be simplest in civil engineering terms, detailed modelling would be needed to understand the consequences of the installation for the sluicing operation. This is examined in detail in Section 8.

7.4.3 Copperhouse Flood Gates Site

In civil engineering terms, Copperhouse Flood Gates site is of intermediate complexity, with a requirement to coffer-dam a greater water area, but without the extensive civil engineering preparatory work needed for Carnsew Culvert Gates. The existing location is shown in Figure 18 below.

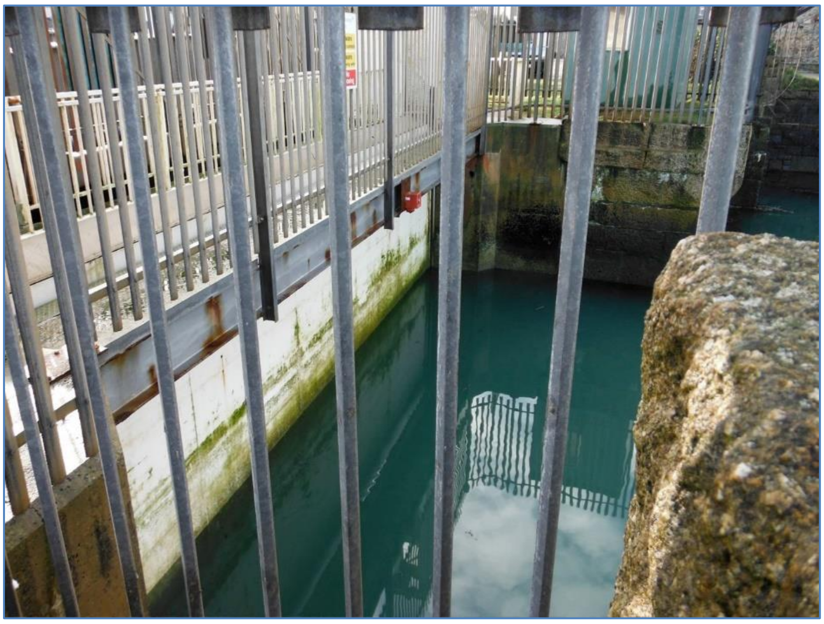

Figure 18: Copperhouse Flood Protection – Existing Site

Copperhouse Flood Protection Gates is comprised of a large steel flood protection gate, in a 10.30m wide and 5.84m in height channel. The gates are of modern design, and generally held at a height of 1.00 m above the channel sill in Summer, and 0.60m in Winter, for flood risk mitigation. The gates can only be operated at slack water (at high water or low water), and do not have the bearing strength for operations whilst significant tidal streams are running through the gate area.

A conceptual illustration of the installation is shown at Figure 19 below, during installation process with the crane gantries in place, and a turbine ready for installation. Note that the Copperhouse bridge has been omitted from Figure 19 and 20, to allow an unobstructed view of the installation concept.

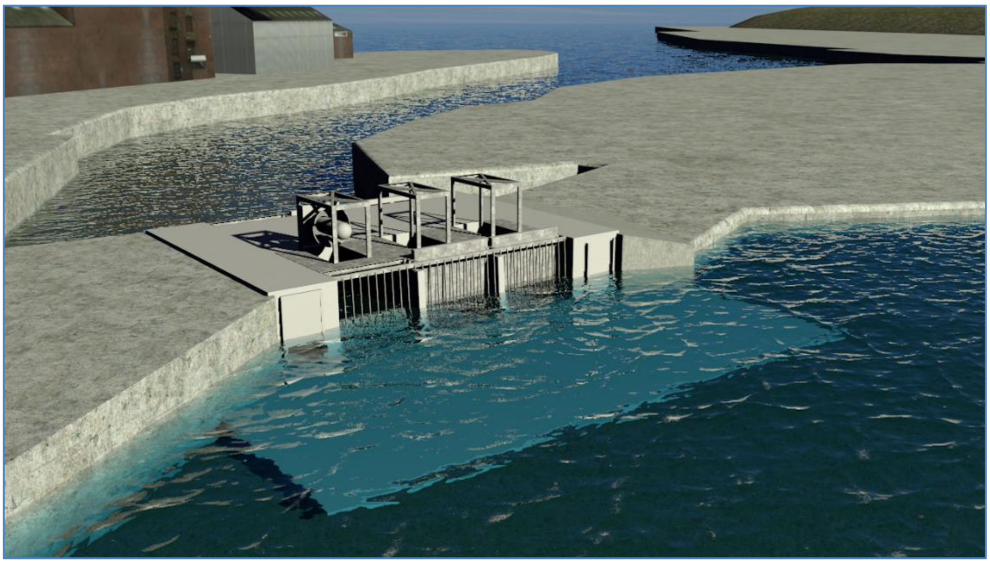

Figure 19: Copperhouse Flood Gates – Pool Perspective

As with the two Carnsew sites, the crane gantries would be removed in the routine operating condition, along the lines in Figure 20.

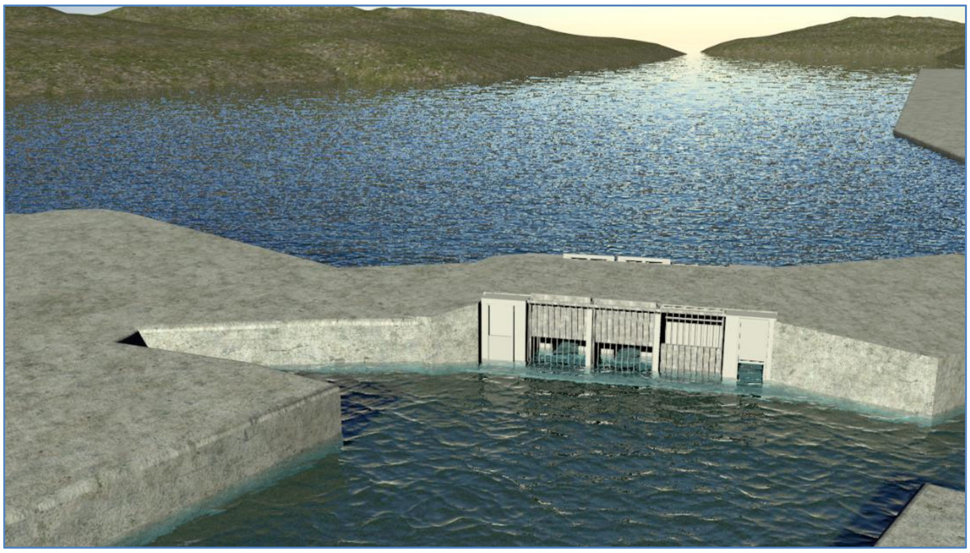

Figure 20: Copperhouse Flood Gates – Harbour Perspective

7.5 Civil Engineering Feasibility Assessment

The preliminary conclusion is that, in civil engineering terms, all 3 sites are feasible, using conventional coastal and inshore engineering methods and cost-effective modular concrete installation units.

Of the sites; Carnsew Sluice Gates site would be the simplest, because of the ease with which the installation can be located in the new lock gate approach; Copperhouse Flood Gates site would be next in complexity, because of the need to coffer-dam more water area; Carnsew Culvert Gates will be the most expensive, thanks to the need for greater civil engineering site preparation.

8 Economic Feasibility

As outlined in Section 5.2 above, the economic feasibility is assessed using 0D LCOE modelling analysis, as set out below, to provide yield inputs to LCOE calculations, drawing on industry standard LCOE modelling developed by CSB Consilium.

It is reemphasized that the turbines used for this modelling analysis are not the StreamDriver turbines used for the civil engineering feasibility analysis above. This is because, first, the StreamDriver is designed for river and 'low-head' hydro applications and does not have the 6 mode operational functionality needed to optimise tidal range energy extraction and, second, the StreamDriver is not designed for salt water coastal locations.

Instead, the chosen turbine is a theoretical bulb turbine, akin to those of large scale tidal range applications such as La Rance and Swansea Lagoon, but theoretically scaled-down for Hayle.

8.1 0D Modelling Analysis

The analytic approach for economic feasibility is to use known/assumed input data in 'zero-dimensional' (0D) modelling to calculate the LCOE cost of energy for a range of different turbine options for both Carnsew and Copperhouse pool. The cost of energy is calculated using:

$$LEC = \frac{aC_I + OM}{E}$$

Where:

- C_I is the capital expenditure (CAPEX);
- OM is the operation and maintenance expenditure (OPEX);
- E is the annual energy yield;

- a is the annuity given by:

$$a = \frac{r(1+r)^N}{(1+r)^N - 1}$$

Where:

- r is the discount rate;
- N is the economic lifetime of the project.

The capital cost is obtained through calculating the cost of a turbine and then assuming, based on hydro-electric and tidal range cost analysis, that: civil installation costs are the same again[9]; O&M costs are 2% of CAPEX.[10]

The energy yield is obtained through the use of the 0D modelling algorithms. These analyse the water depth on either side of the tidal barrage to establish the 'head', then calculate the energy yields by considering the flow rates through the turbines throughout a year, based on optimising that flow for either dual-mode, ebb-mode or optimised-mode[11]. The fundamental equation used in this model is:

$$S(z)\frac{dz}{dt} = Q(H)$$

Where:

- z is the basin water level;
- t is the time;
- S(z) is the surface area of the basin at the water level z;
- Q(H) is the flow in or out of the basin for the water head difference barrage wall, H.

The 0D modelling approach used discretizes the water level within the basin, and then calculates every possible flow path throughout the year and chooses the optimal for energy yield. Flow path regulation is achieved through adjusting the operation of the theoretical turbine, by energy extraction, pumping, or sluicing.

The input data required for the model is: external tide (which may be obtained from a time series or the site tidal constituents); site bathymetry; turbine performance characteristics and price; sluicing capacity.[12]

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9 CAPEX costs in this study do not include development costs; these are generally assumed to be a further 10% of CAPEX.

10 See, for example, *Hydropower, Volume 1: Power Sector, Issue 3/5*, dated June 2012, International Renewable Energy Agency, p.22, p.25.

11 Dual-mode assumes that power is generated on both flood and ebb tides; ebb-mode assumes that power is generated only on the ebb tide; optimised-mode assumes that control algorithms are employed to optimise the balance between flood tide and ebb tide, so as to maximise the energy capture.

12 The energy model divides the water level within the basin into discrete levels, in this model 1cm levels. It then calculates the energy yield obtained when moving from one level to every other level that can be reached. This means that it can use both the turbines and sluice gates whenever it chooses, and indeed the paths of using both and only one each is calculated at every time step throughout the year. At the end of the year, the model selects the path that produced the greatest energy yield. As a result, there are times when both the sluice gates and turbines are being used. This is because the algorithm found that the loss of energy on the tidal phase where the sluicing took place was counter-balanced on the next phase through extra energy generation.

8.2 Input Data

The limited budget did not allow detailed oceanographic or bathymetric survey to be undertaken, thus the input data was thus obtained from alternative sources.

8.2.1 External Tide

The external tide data was deduced from pressure sensor data[13] used to support academic research in 2006. Pressure sensors installed in Hayle Harbour, external to both pools, provided continuous tidal height data for a 35-day period from the 19th December 2006, as shown at Figure 21 below.

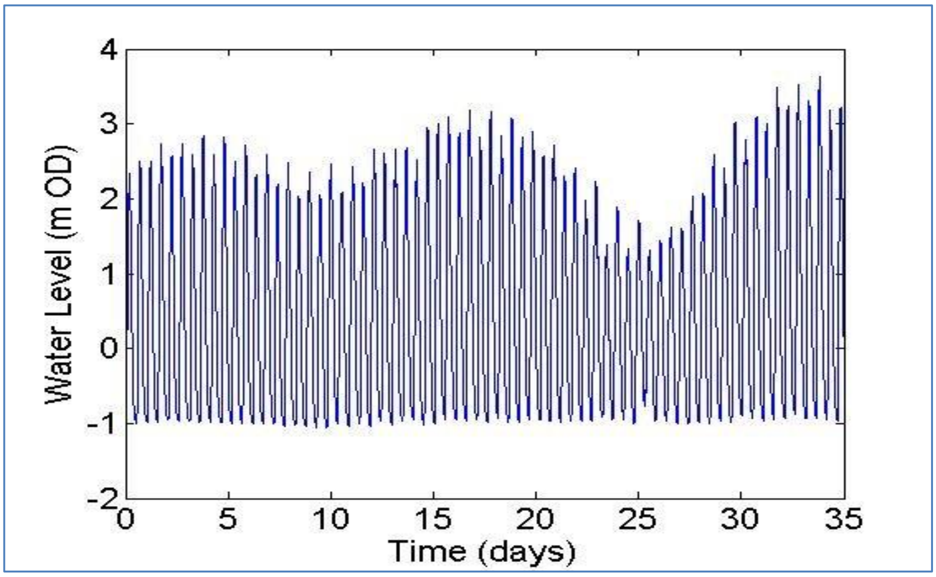

Figure 21: Tidal Time Series – Hayle Harbour, Dec 06

The observed water levels are plotted relative to Ordnance Datum (OD), across the 35-day time series. This shows, from inspection, that the tide is asymmetric, which in turn suggests the presence of a number of shallow water tidal constituents[14].

The tidal constituents were extracted from the data, using the 't_tide' software package. This permitted a year-long time series to be deduced, for external tide input in the LCOE energy generation modeling. Figure 22 shows a comparison of the observed and modelled data for the first few weeks of January 2007.

13 University of Plymouth, *Harnessing the Power of the Tide: A Tidal Scheme Proposal for Carnsew Pool, Hayle*, dated January 2007.

14 A tide in a particular region or location is calculated through the use of a number of tidal 'constituents', each a function of particular gravitational influences.

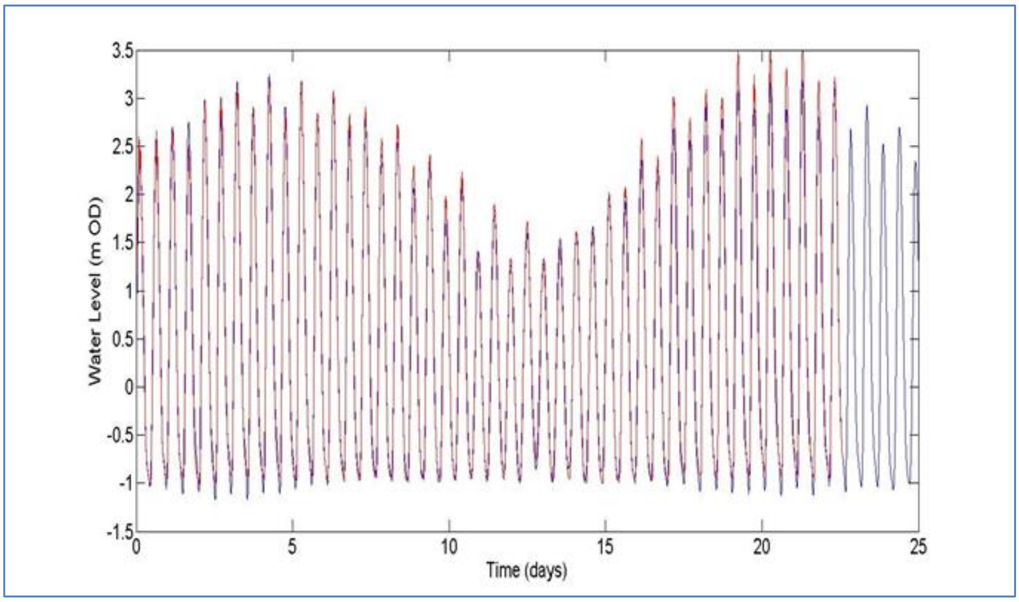

Figure 22: Tidal Time Series – Observed v Model Output

Observed data (red) and modelled data (blue) blue are very close, and the model outputs are thus judged acceptable for LCOE modelling.

8.2.2 Bathymetry

The basin bathymetry was deduced from the LIDAR[15] data shown in Figure 23. This data is open source Environment Agency data, and of high resolution (0.5m), and ideal for a feasibility analysis of this nature.

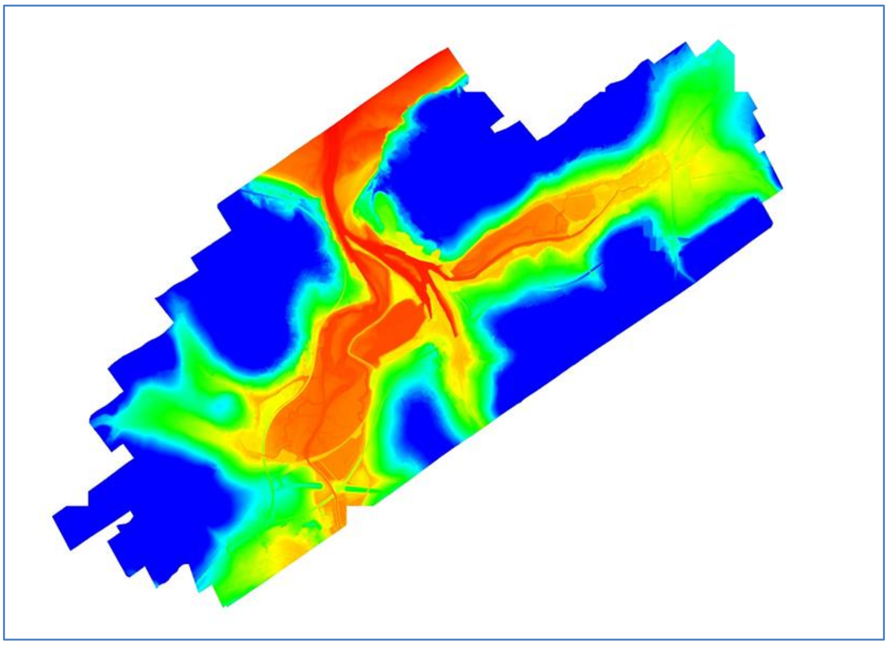

Figure 23: Hayle Estuary & Harbour – LIDAR Data

The 0D model requires the surface area, as a function of water level, which was extracted from the LIDAR data and is shown in Figure 24 below. This shows how the surface area of the two pools (Carnsew in blue and Copperhouse in red) changes as the water level in the pool drops.

15 Light Detection And Ranging, which uses aerial mapping.

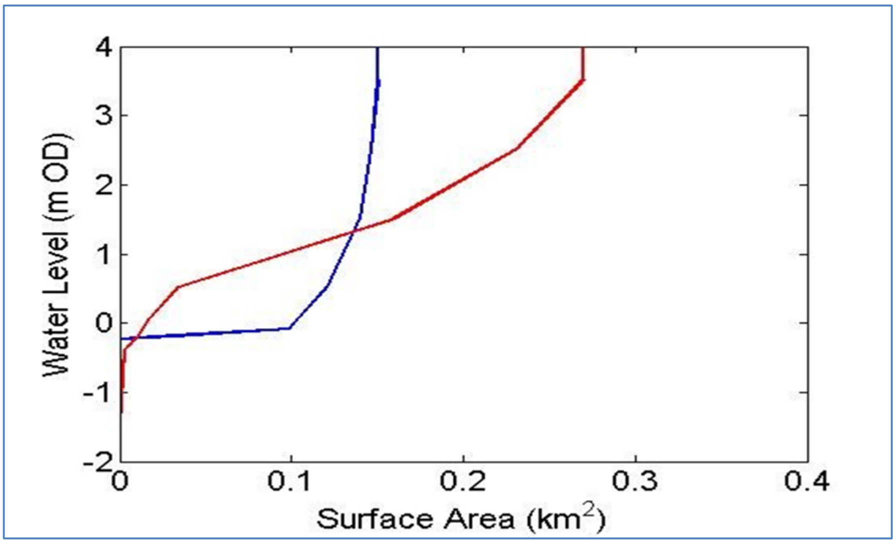

Figure 24: Carnsew & Copperhouse – Pool Depths v Pool Areas

This is an important plot, and demonstrates that, **although Copperhouse has a higher surface area when full, the pool volume decreases very rapidly to a small channel (originally excavated as a canal in 1770) as the sea level falls. Whereas there is very little change in the depth of Carnsew pool until the bottom of the pool is reached.**

The annual potential energy from both pools is calculated as:

- Carnsew Pool 1,911MWH
- Copperhouse Pool 1,497MWH

The lower energy potential in Copperhouse Pool is a result of the rapid change in surface area with depth, whereas the Carnsew Pool remains at a consistent area with depth. From this, it is immediately clear that, of the two pools, **Carnsew represents a better total energy prospect than Copperhouse.**

8.2.3 Theoretical Turbine Performance

The turbine performance used for the analysis have been derived from a publicly available double-regulated bulb turbine hill chart[16], as routinely used in large scale *tidal range* LCOE analysis, as shown at Figure 25 below.

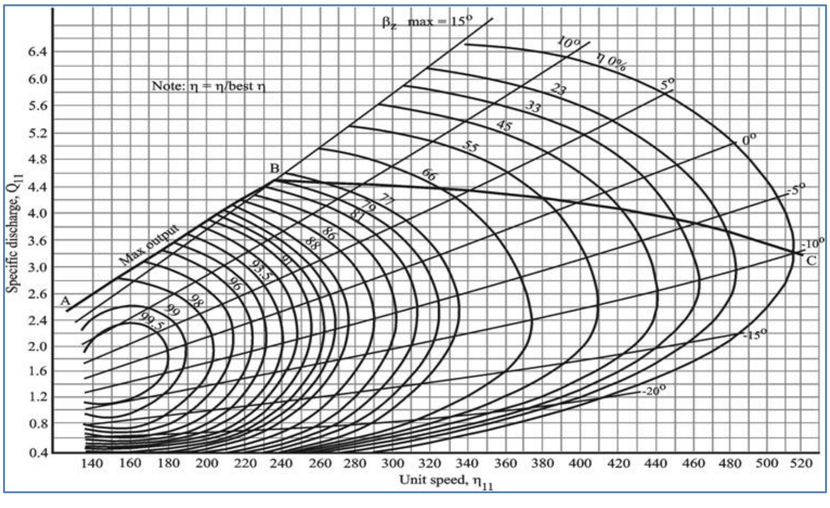

Figure 25: Double Regulated Bulb Turbine Hill Chart

16 Tidal Power, Baker, A.C., London, 1991, Figure 3.11, p53.

The complication of the Hayle site – and the site of many other former tide mills – is that the turbine operating paths in Figure 25 assume that the turbine is always submerged. This is not the case for Hayle, because the turbines will 'dry' at low tide. **There is no research literature available on the use of turbines 'drying' in tidal range schemes, and this is an area for future exploratory research into the retrofit of micro and mini tidal range power schemes.** Pending such research, maximum theoretical turbine efficiencies were reduced to relatively low levels with: 80% in the 'direct flow direction' (ebb-tide); 64% in the 'reverse flow direction'[17], (flood tide). This reduction is used for all 3 Hayle site analyses, to reflect the loss of power due to turbines drying.

To better understand the optimum theoretical turbine requirement for the Hayle site(s), 3 different theoretically scaled-down bulb turbines were used in the modelling, as shown in Table 1 below.

Theoretical Turbine	Rated Power	Diameter
1	250 KW	2.0m
2	60 KW	1.0m
3	30 KW	0.5m

Table 1: Theoretical Turbine Characteristics

As will be demonstrated, the higher efficiency in the direct flow direction means that a lower discharge rate is required to achieve the rated power output. It also means that the rated power is reached on a smaller head.

8.2.3.1 Theoretical Turbine 1 – 250KW – Operating Profile

For Turbine 1, rated at 250KW, the 'direct flow direction' rated-head is 1.63m, which is just below the M_2 tidal amplitude of 1.72m. In accordance with the applied scaling factor, the cost of this turbine is set at £838K per unit.

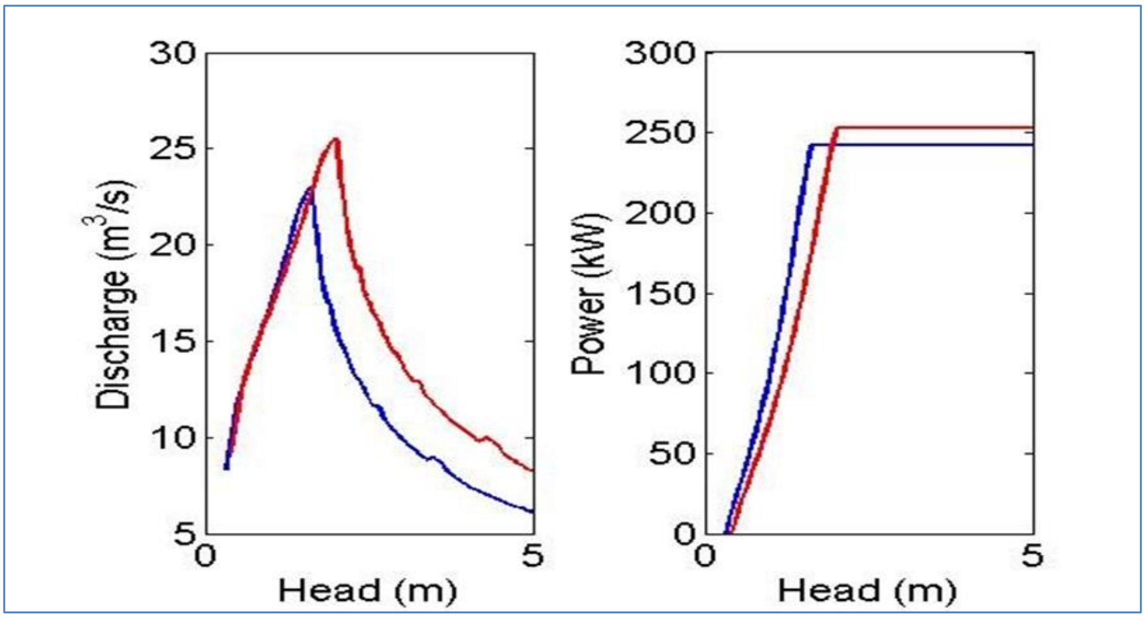

Figure 26: 250KW Turbine – Power Curves

[17] See Section 5.2.1.

The operating path plot for 250kW turbine is shown at Figure 26: left panel shows the flow rate against head and the right panel shows the power output, with direct flow direction (blue) and reverse flow direction (red).

8.2.3.1 Theoretical Turbine 2 – 60KW – Operating Profile

For Turbine 2, rated at 60KW, the 'direct flow direction' rated head is again 1.63m, which again is just below the M_2 tidal amplitude of 1.72m. In accordance with the applied scaling factor, the cost of this turbine is set at £214K per unit.

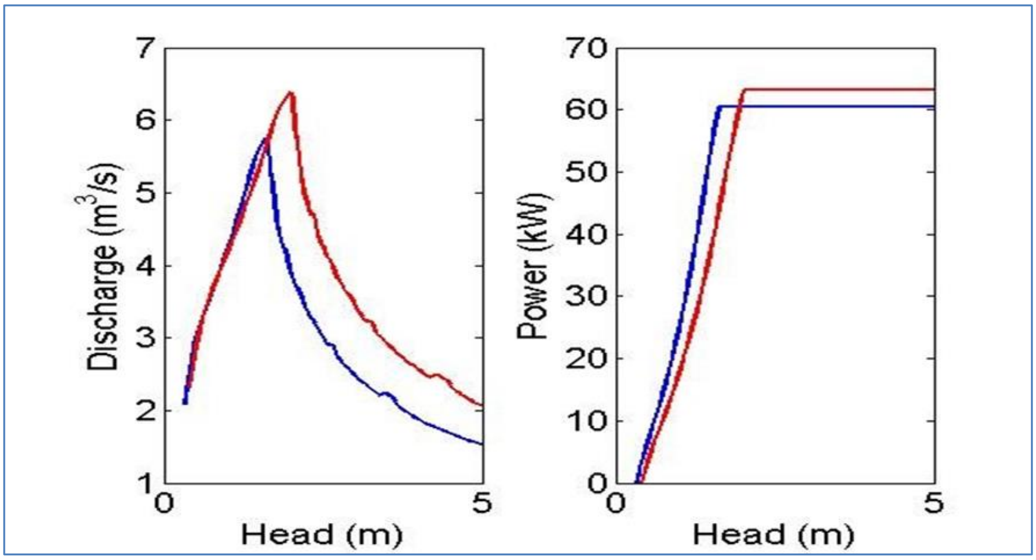

Figure 27: 60KW Turbine – Power Curves

The operating path for the 60kW turbine is shown at Figure 27 above; again, the left panel shows the flow rate against head and the right panel shows the power output, with direct flow direction (blue) and reverse flow direction (red).

8.2.3.2 Theoretical Turbine 3 – 30KW – Operating Profile

For Turbine 3, rated at 30KW, the 'direct flow direction' rated head is now 2.55m. In accordance with the applied scaling factor, the cost of this turbine is set at £56K per unit.

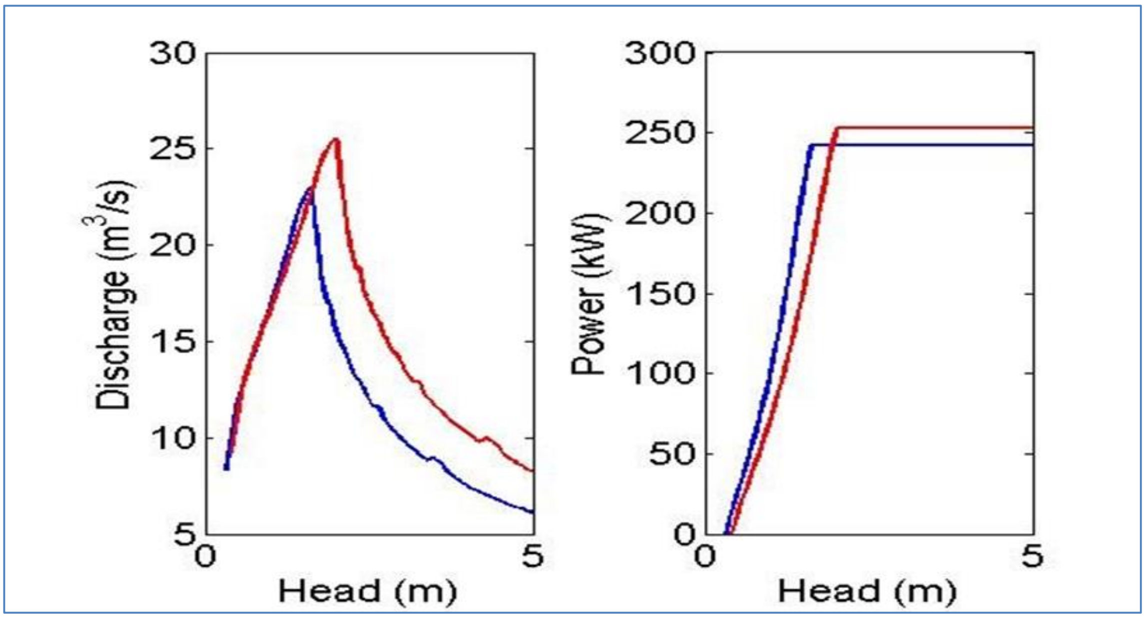

Figure 28: 30KW Turbine – Power Curves

The operating path for the 30KW turbine is shown at Figure 28 above; again, left panel shows the flow rate against head and the right panel shows the power output, with direct flow direction (blue) and reverse flow direction (red).

8.2.4 Sluicing Characterisation

The sluices modelled in the 0D model are assumed to be open channel flows, with maximum site widths and site sill level as outlined in Table 2 below.

Site	Width	Sill Level (v OD)
Carnsew Sluice Gates	9.5m	-0.1m
Copperhouse Flood Gates	10.3m	-0.5m

Table 2: Sluicing Model Input Data

Within both pools, where a turbine is placed in the opening currently occupied by the culvert or sluice gates, it is assumed that the gates width will be reduced by an equivalent amount to the space taken up by the turbine installation, as detailed in Sections 8.3.1 to 8.3.3 below.

The importance of the sluicing data is that the 0D modelling works by optimizing the flows into and out of the pools, either for power generation or to fill or empty the pools by sluicing so as to improve overall energy capture across the full tidal cycle.

8.3 0D Modelling

As set out in Section 8.1 above, the 0D modelling works by discretising the water level in the pool, then calculating every possible option of power generation, pumping or sluicing throughout the year, and choosing the optimal path. It is for this reason that it is important to understand the sluicing capacity of the schemes. Note that the analyses examine the yield from just the Carnsew and Copperhouse Pools, and does not differentiate between the 2 different civil engineering installation sites within Carnsew, examined in Section 7 above.

8.3.1 Carnsew Pool – Single Turbine Analyses

The optimized LCOE for each of the 3 theoretical turbines is given in Table 3 below.

Turbine	Rated Power (KW)	LCOE (£/MWH)	Turbine Nos	Sluice Width (m)	Energy (MWh)	CAPEX (£000's)	Intertidal Area Retained (%)
1	250	£ 186.00	1	8.5	956.0	£ 1,716.0	99.35%
2	60	£ 133.00	1	9.5	335.0	£ 428.0	97.57%
3	30	£ 84.00	1	9.5	139.0	£ 112.0	21.35%

Table 3: LCOE Model Data Carnsew Pool

As Table 3 shows, for each theoretical turbine size, the cheapest LCOE is obtained using a single turbine[18]. It is also the case that the smaller the turbine the lower the LCOE: this is as anticipated, given that the enclosed volume of water is relatively small. The cheapest LCOE is £84 MWH^{-1}, using the 30KW turbine, which is extremely competitive for marine renewable energy.

Sensitivity analysis is undertaken, adopting a more pessimistic view by increasing CAPEX by 10% and reducing yield by 10%, and shows that an LCOE of £102 MWH^{-1} could still be obtained, again still extremely competitive.

18 This is in part because the 0D model scales the turbine civil engineering costs linearly with turbine numbers. This is a pessimistic assumption, and in practice the average civil costs per turbine are likely to reduce with increasing turbine numbers, but this assumption is sufficient for the purposes of this high level feasibility study.

Because it has the lowest LCOE, the 30KW turbine analysis is examined in more detail. Figure 29 shows the water levels within the Carnsew Pool, the left panel with a yearlong time series and the right panel the first 5 days; the external tide is in blue and the basin water level is in green.

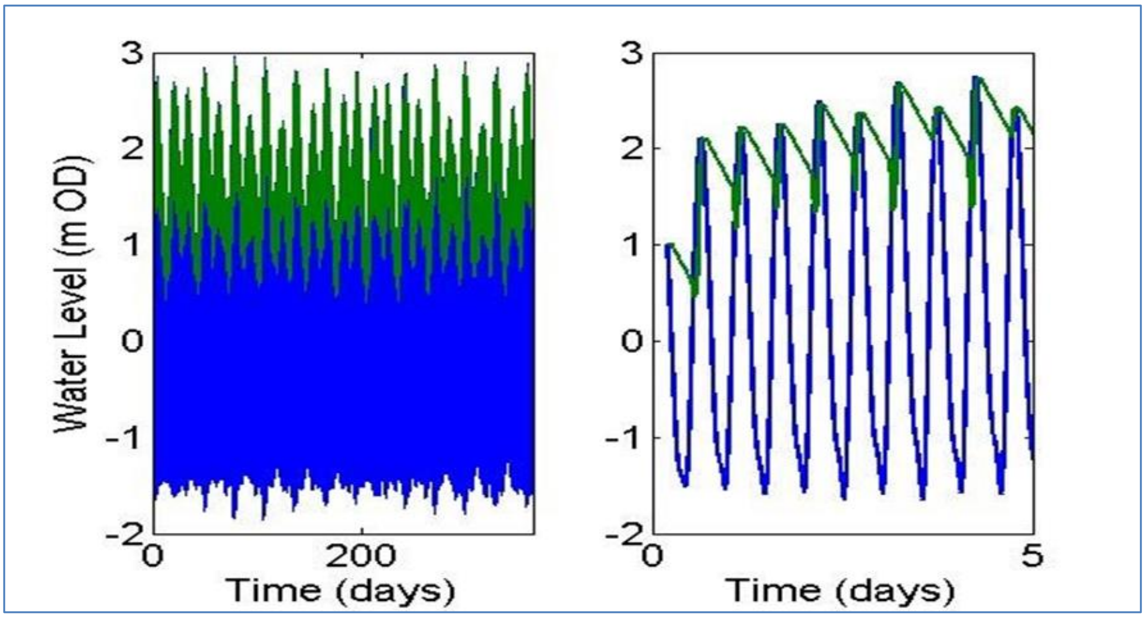

Figure 29: 1 x 30KW Turbine – Carnsew Pool Water Levels

The key problem with the 30KW turbine is the loss of nearly 80% of the intertidal[19] areas. The retention of around 21% of the original intertidal area is due to power optimization, with the optimization algorithm maintaining high water level within Carnsew in the manner of a standard single mode ebb-only operation tidal range.

The key factors driving this optimization solution are:

- the low discharge rate of the small 30 KW turbine;
- the relative inefficiency of the 30KW turbine in the 'reverse flow direction' during the flood phase and, thus, the algorithm's preference for ebb-tide power generation.

In essence, maintaining a higher head during the ebb-phase maximizes the energy yield for the longest ebb-tide generation window, but also reduces Carnsew Pool's interior tidal range, and thus gives rise to the significant loss of intertidal zone. This is likely to be an issue for the RSPB, thus an adjusted modelling with 4 x 30KW turbines is examined at Section 8.3.3 below.

Power outputs from the turbine are shown at Figure 30, again with a yearlong series in the left hand pane and the first 5 days in the right hand pane.

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19 For the purposes of this report, the Intertidal area is defined as the difference in wetted surface area of the enclosed basin(s) between the highest and lowest tidal levels of the year. This is calculated by taking the highest and lowest tide levels of the year, and using the bathymetry curve (Figure 24) to calculate the basin surface area between these two levels.

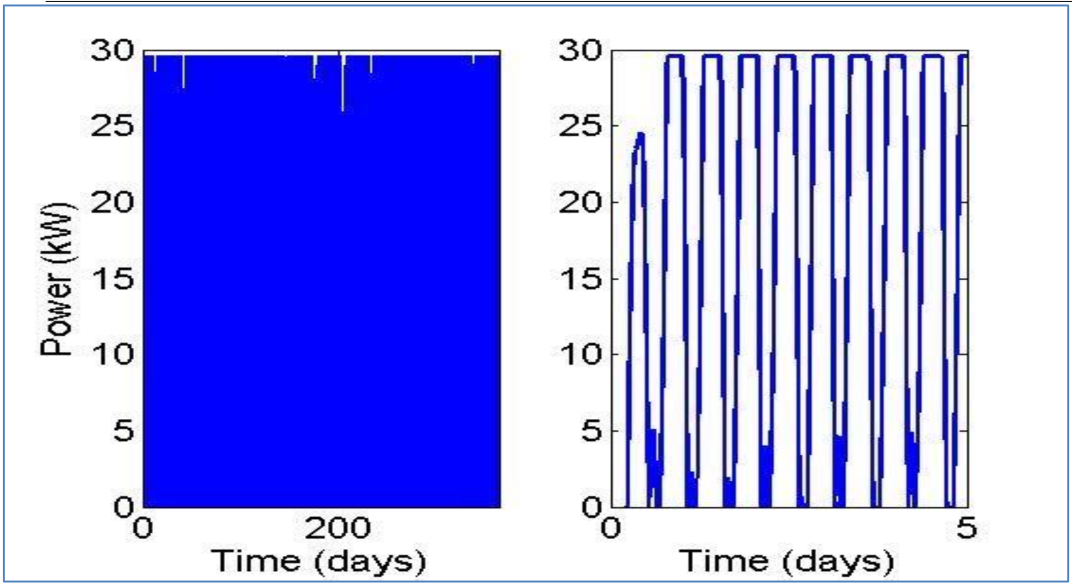

Figure 30: 1 x 30KW Turbine – Carnsew Power Output

The power output has a pattern akin to an ebb-only tidal range scheme. The energy is clearly seen to come in single large blocks during the ebb tide, with a small power pulse during the flood phase of the tide. Note also that the power reaches the rated level for nearly every tide, even during neap tides, suggesting that the theoretical turbine is under-rated.

8.3.2 Copperhouse Pool – Single Turbine Analyses

For Copperhouse Pool, the optimized LCOE for each of the 3 theoretical turbines is given in Table 4 below.

Turbine	Rated Powe (KW)	LCOE (£/MWH)	Turbine Nos	Sluice Width (m)	Energy (MWh)	CAPEX (£000's)	Intertidal Area Retain
1	250	£ 225.00	1	5.0	793.0	£ 1,716.0	99.93%
2	60	£ 136.00	1	7.5	326.0	£ 428.0	99.74%
3	30	£ 82.00	1	9.0	141.0	£ 112.0	99.00%

Table 4: LCOE Model Data – Carnsew Pool

As with Carnsew Pool, the small 30KW turbine has the cheapest cost of energy at £82 MWH^{-1}.

When conducting the same sensitivity analysis as Carnsew, adopting pessimistic view figures by increasing CAPEX by 10% and reducing yield by 10%, an LCOE of £101 MWH^{-1} is obtained, again still extremely competitive. Lowest LCOEs are again achieved for all the theoretical turbines when only single turbine units are installed.

Note though that these figures do not take account of the EA's need to close Copperhouse Pool on occasion for flood protection. The number of closures is dictated by flood risk, which is in turn governed by tidal range height, and offshore and onshore weather conditions. Probability risk modelling was beyond this report's scope, but the feedback from the Harbour Master is that the gates are closed on average between 5 and 10 days per annum. Thus although the Copperhouse LCOE for the 30KW turbine appears marginally to favour Copperhouse over Carnsew, the Copperhouse figure needs to be adjusted upward to reflect the loss of yield in Copperhouse during flood protection days.

Again, because it has the lowest LCOE, the 30KW turbine analysis is examined in more detail. Figure 27 shows the water levels within the Copperhouse Pool, the left panel with a yearlong time series and the right panel the first 5 days; the external tide is in blue and the basin water level is in green.

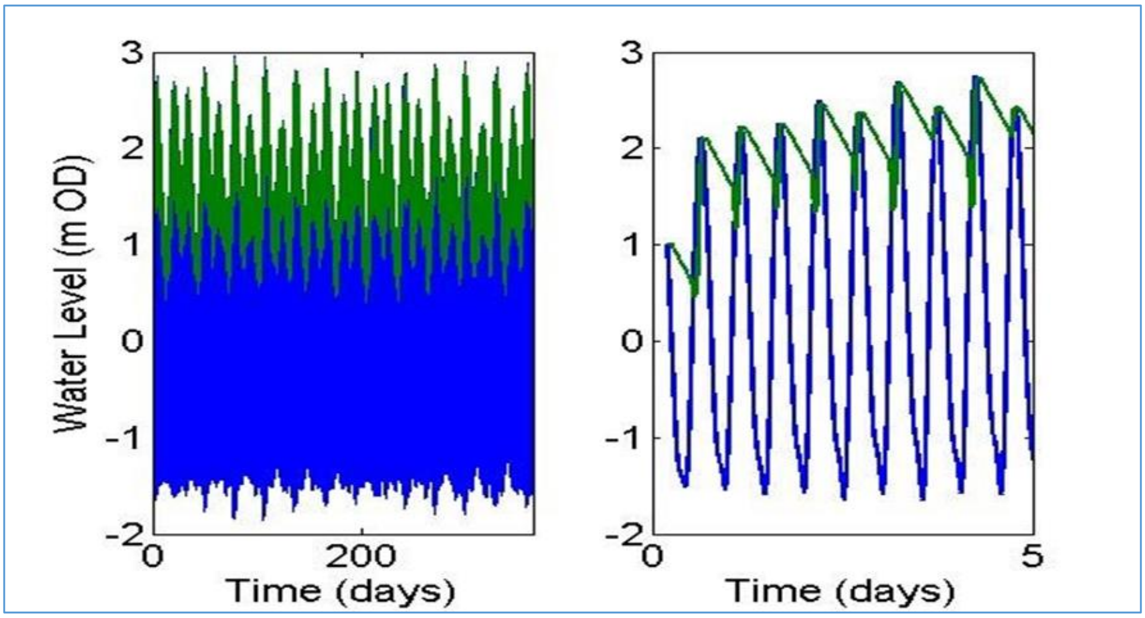

Figure 31: 1 x 30KW Turbine – Copperhouse Water Levels

The water levels within Copperhouse Pool again follow a pattern akin to the ebb-only operating mode, with the optimization algorithms maintaining high water levels within the pool to maximize energy yield.

Unlike Carnsew though, when neap tides occur the water level decreases to a much greater extent due to the rapid change in bathymetry within the basin. The advantage of maintaining the tidal range within the pool is that the intertidal area over the year is retained at higher levels, thus with less overall environmental impact.

Because this approach would necessarily require a change in the operational mode of the EA Flood Protection regime, there might actually be an increase in the inter-tidal area in Copperhouse over the year, with potential environmental and societal benefits. Such a change would require an agreement by the EA to the different operating regime, though, and would need also be the subject of more detailed resource and coastal modelling analysis. There would also be a need to examine and ensure that, after installation of tidal range turbines, the flood protection capacity of Copperhouse Pool was, as a minimum, maintained at its current levels: this too would need to be examined in detail, in cooperation with the EA.

Because it has the lowest LCOE, the 30KW turbine analysis is again examined in more detail. Power outputs from the turbine are shown at Figure 32, again with a yearlong series in the left hand pane and the first 5 days in the right hand pane.

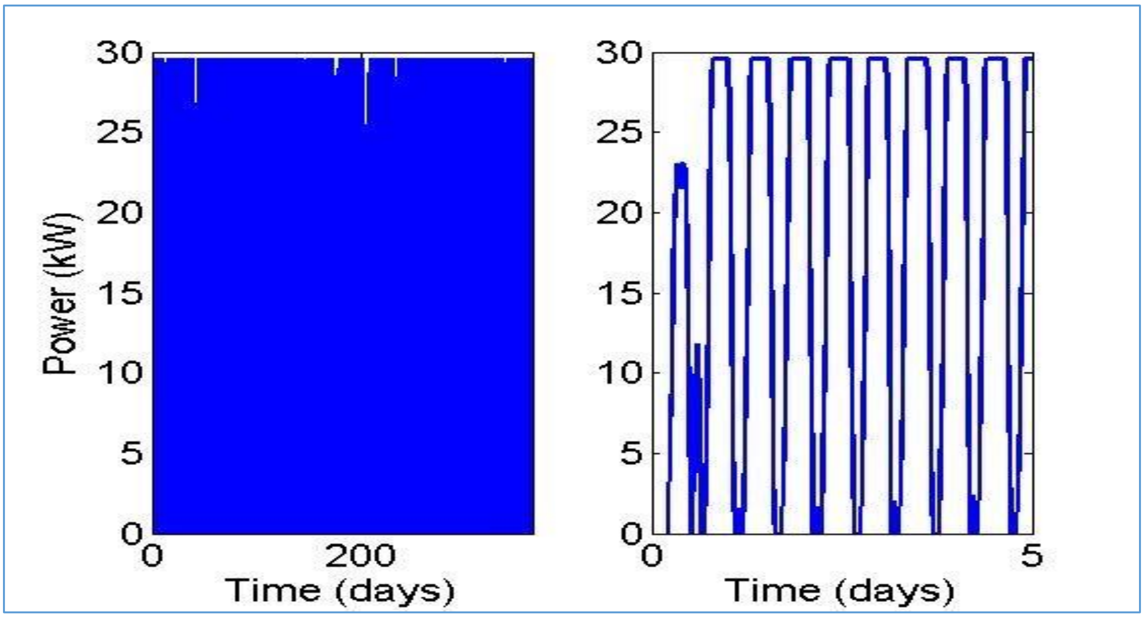

Figure 32: 1 x30KW Turbine – Copperhouse Power Output

Again, the power output has a pattern very akin to an ebb-only tidal range scheme. Power output reaches the maximum for nearly every tide, suggesting again that the theoretical 30KW turbine would be under-rated. The timing of the power output is even more clearly seen during the ebb phase, with only very small pulses during the flood tide.

8.3.3 Carnsew Pool – 4 x 30KW Turbine Analysis

Whilst the LCOE is minimized for a single 30KW turbine, the loss of intertidal area is significant. This loss could, though, be largely eliminated by the use of more 30KW turbines. For this reason, a further option is examined, with 4 x 30KW turbines installed in the Carnsew Culverts, with sluicing through Carnsew Sluice Gates.

It is important to note that, in this particular modelled scheme, the turbines and sluice gates are assumed to be operating in an integrated way, with the sluice gates forming an integral part of the tidal range energy generation system.

The modelling assumes that the Carnsew Culvert site is fitted with 4 x 30KW turbines and that the Carnsew Sluice Gates, which have recently been refurbished, operate as a standard *tidal range* sluice. The sluice was modelled as an open channel weir, with a width of 9.5m and a sill depth of -0.1m MSL which is 0.384m OD. The 0D model output is shown at Table 5 below.

Turbine	OPEX Assumed	Rated Powe (kW)	LCOE (£/MWh)	Turbine Nos	Sluice Width (m)	Energy (MWh)	CAPEX (£000's)	Intertidal Area Retained (%)	Pessimistic LCOE (£/MWh)
3	100%	30	£ 98.16	4	9.5	474	448	99.76%	£ 119.98
3	75%	30	£ 85.89	4	9.5	474	392	99.76%	£ 104.98
3	50%	30	£ 73.62	4	9.5	474	336	99.76%	£ 89.98

Table 5: LCOE Model Data – Carnsew Pool

As Table 5 shows, the LCOE rises, but so too does the overall energy project energy capture. The overall project yield is 474MWH, with the potential to provide annual power for 146 homes[20]. As before, the LCOE of £98 MWH^{-1} is still very cost effective, compared to large scale *tidal range* LCOEs.

The sensitivity analysis using the pessimistic figure, assuming increase in CAPEX by 10% and reduction in yield of 10%, of £120 MWH^{-1} is still significantly lower than large scale *tidal range* schemes.

20 Based on OFGEM annual consumption value of 3.3MWH per UK domestic home. https://www.ofgem.gov.uk/ofgem-publications/64026/domestic-energy-consump-fig-fs-pdf

Table 5 also includes LCOE sensitivity analysis to examine the impact of assuming that the CAPEX(Civil) falls as a percentage for CAPEX(Turbines) from 100% to 75% and 50% respectively. This shows that, if civil engineering costs can be reduced, then LCOE's in the range £86 to £74 MWH^{-1} would be achieved.

The water levels within and without the Carnsew pool are shown in Figure 33 below. The current minimum water level is -0.6m MSL due to the weir by the Carnsew Culverts. This implies a loss of intertidal habitat of: on Neap tide (i.e. minimum), around 10 hectares; on Spring tides (i.e. maximum), around 12 hectares.

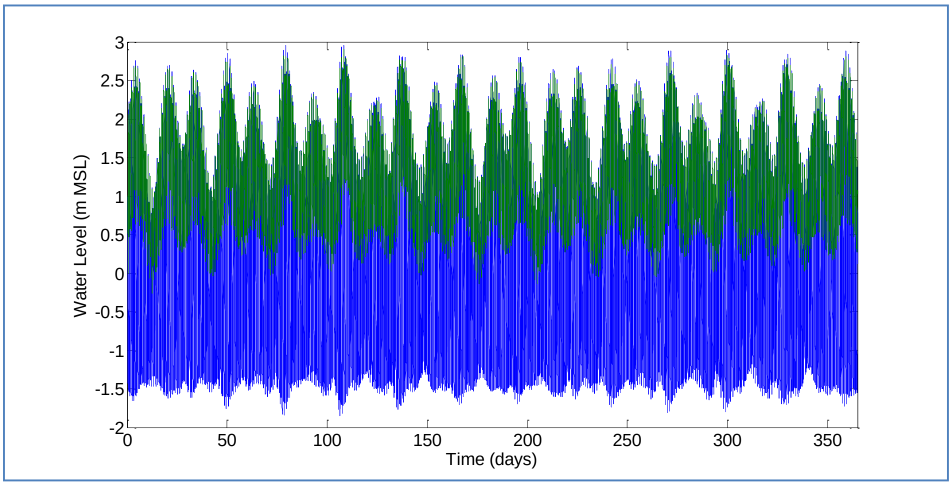

Figure 33: Carnsew 4 x 30KW - Annual Water Levels

The change in water level in Carnsew for this scheme is shown in detail for a Spring tide period from the 19th to 21st January 2007 in Figure 34 below.

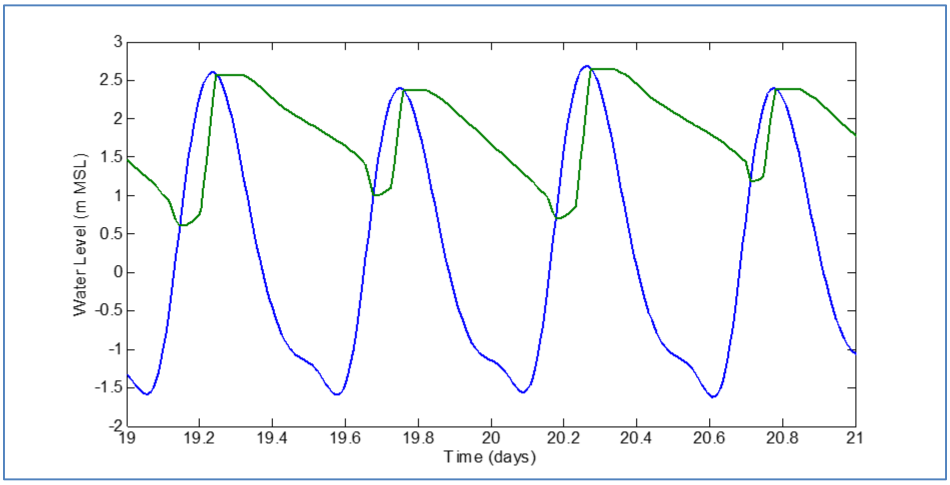

Figure 34: Carnsew 4 x 30KW – Water Levels 19-21 Jan 07

This shows how the optimization algorithm maximizes energy capture with:

- ebb-tide phases – long discharge periods through the turbines, when the majority of the electricity generation takes place, followed by short periods of sluicing;
- flood-tide phases – a short period of power generation takes place, followed by a rapid sluicing through the sluice gates to fill up the pool and regain a large head for the next ebb tide phase of energy generation.

The balance of flow between the turbines and the sluice gates are shown in Figure 35 below.

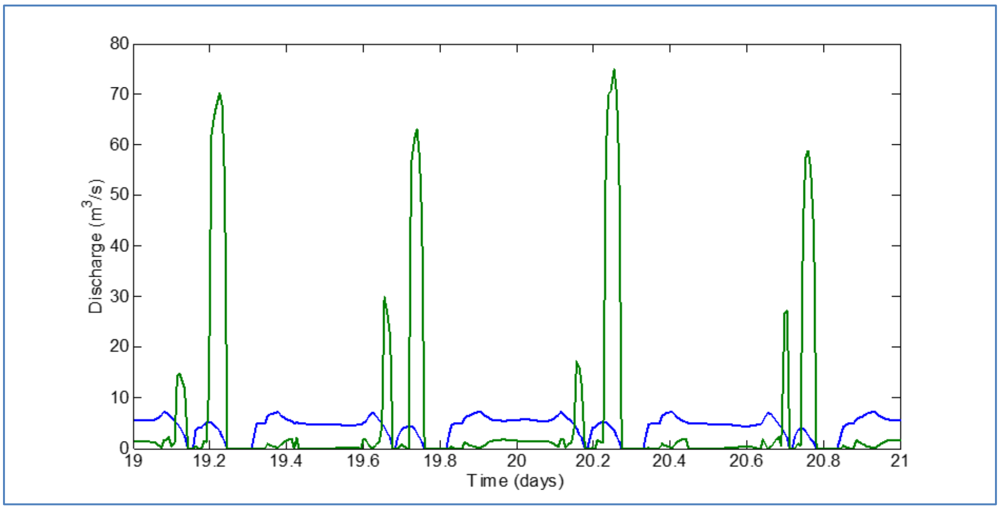

Figure 35: Carnsew 4 x 30KW – Balance of Flow between turbines (blue) and sluices (green)

The turbine flow rates, shown in blue, are relatively small volumetrically, and occur in two phases. The first is a long period where the ebb-phase power generation occurs; a second smaller phases occurs during flood-phase power generation.

The sluice flow rates, shown in green, also occur in two distinct phase, both with high flow volumes. The first, and smaller peak, is the discharge at the end of the ebb-tide phase; while the second and larger peak is the filling of the pool during the flood-tide phase.

It can be clearly seen that the turbine and sluice gates sometimes operate at the same time. This is so that the maximum energy during each phase may be extracted, but also to allow for a larger amount of energy to be generated during the next tidal phase.

Power outputs from the turbine are shown at Figures 36 (2 days) and 37 (1 year) below.

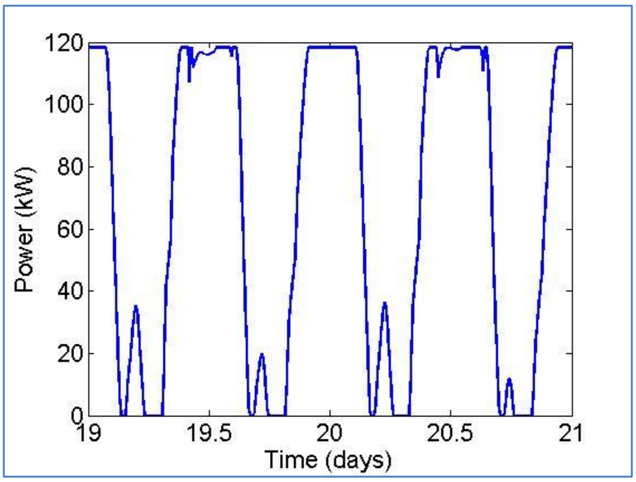

Figure 36: Carnsew 4 x 30KW – Power Output 2 Days

Again, the power output has a pattern akin to an ebb-only tidal range scheme. The energy is clearly seen to come in single large blocks during the ebb-tide phase, with a small power pulse during the flood-tide phase.

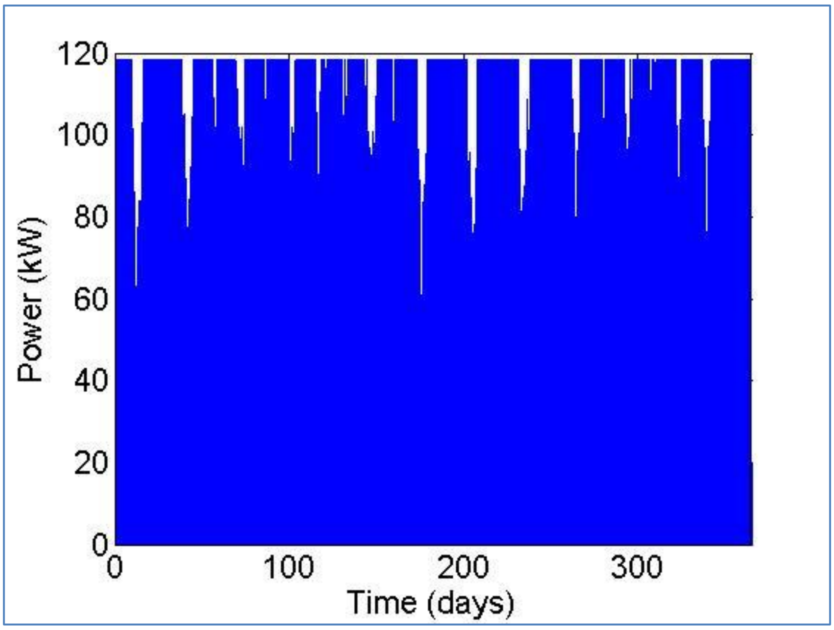

Figure 37: Carnsew 4 x 30KW – Power Output 1 Year

Again note that the power reaches the rated level for nearly all annual tides, even during Neap tides, again suggesting that the theoretical scheme may be under-rated.

8.4 Economic Feasibility

It is clear from the above analysis that, **when looked at solely from a tidal range power generation perspective, both Copperhouse and Carnsew Pools are economically feasible, providing that existing bulb turbine technologies can be developed of the right installed power, size, operating mode, modularity, and cost. It is also clear that such technologies would be capable of use in a range of former tide mills and/or new micro or mini tidal range schemes. Last but not least, the LCOEs of such schemes appear very competitive, compared to other offshore renewable energy LCOE**.

Detailed investment appraisal, using standard techniques – such as payback period, net present value, and internal rate of return - would need to be undertaken on as yet unknown information – such as the weighted average cost of capital, likely strike price for tidal range electricity, and critically the investor risk appetite for offset technologies that are not yet in R&D.

Nevertheless, from a high level investment appraisal perspective, based on the input assumptions, the project is investable, and worthy of detailed technological and investment appraisal analysis. Specific site caveats are to do with the unique characteristics of the Hayle site, in particular the (potentially competing) needs of sluicing and flood protection, which are explored in more detail in Section 9 below.

9 Scheme Impacts

This reports purpose is to assess civil engineering and economic feasibility of the scheme(s), not the broader non-technical impacts, be they environmental, social or economic. This is achieved by drawing on the feasibility analysis – civil engineering and economic – but also undertaking coastal modelling. This section of the report thus draws attention to scientific and technical findings that have potential environmental, social and economic impacts, but does not make detailed value judgements about these impacts.

'Coastal modelling' is an industry term used to describe the scientific modelling, using computational fluid dynamics, of coastal and estuarine locations using industry standard packages such as Mike21 and Delft3D. Drawing on bathymetric data, these models discretize a modelled area into geographic 'cells', and then solve fluid dynamic equations across the cell borders to provide a basis for impact analysis, for example in the construction of new barriers upon sedimentary movement.

Delft3D has been used in this report to model Carnsew and Copperhouse Pools, the broader Hayle Estuary including the navigable channel, so as to gain insights into the oceanographic impact of the scheme(s). Because of the limited budget, coastal modelling for this project was necessarily high level and preliminary, but nevertheless provided useful insights into the broader scheme impacts.

9.1 Coastal Modelling

9.1.1 Coastal Model

The coastal model was developed according to the following inputs:

- boundary conditions – were derived from UKHO Total Tide water level predictions for St Ives;
- bathymetry – were sourced as follows:
    - below inter-tidal areas – seaward of the estuary mouth were derived from available datasets available from UKHO Inspire;
    - inter-tidal areas – both in the estuary and around its mouth, were derived from EA LIDAR data, outlined at Section 8.2.2 above. The LIDAR acquisition was flown around LW springs, thus good coverage was achieved;
    - estuary channels – these represented a very small part of the tidal prism, and were not measured by LIDAR[21]. The channel depths were thus incorporated manually, based on advice from the Harbour Master[22]. For this reason, the model outputs were produced in the form of predicted difference in relative flow speeds between scenarios, rather than absolute flow speeds.

The coastal model grid[23] is shown at Figure 38 below.

21 LIDAR does not penetrate the water surface, except in very clear waters.

22 As the report was being finalized, new bathymetric data became available which included a new hydrographic survey of the estuary. This data could be interpolated into the model for future work, but in the meantime the modelled flow speeds in the channels were treated with a degree of caution.

23 The grid is the division of the model the process of dividing the model area into a large number of computational elements, or "cells". For each instant in time the model calculates the water level and current velocity in each cell, and propagates the calculated values to that cell's neighbours where the same calculation is again performed. This drives a solution across the whole model domain, which is then repeated for the next time step until the required time-frame has been completed. Correct gridding is critical since it: determines the resolution of the model, and hence the model accuracy; optimises computational efficiency

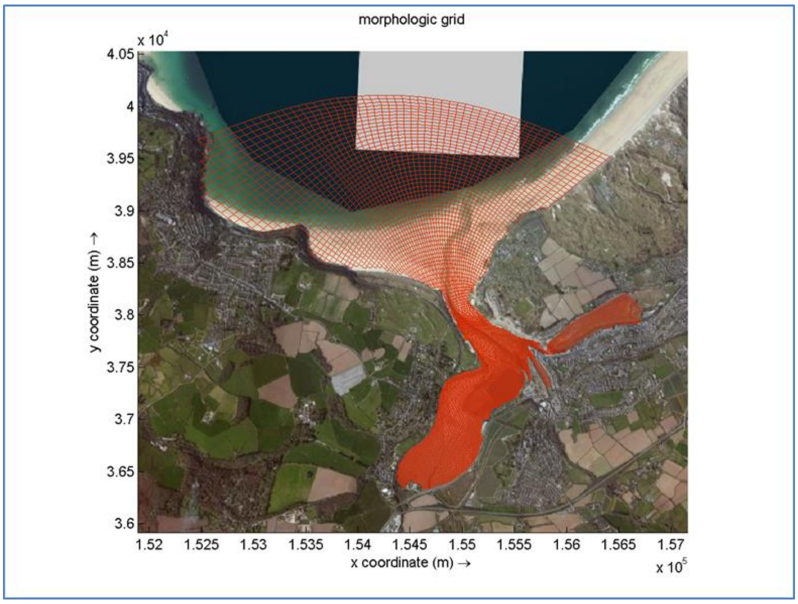

Figure 38: Coastal Model Grid

Cell resolution increases from approximately 75m at the open sea boundary, to approximately 10m in the area of interest. Adjustment of the sea bed roughness parameter was the primary means of model calibration[24].

The preliminary calibration was carried out against local water levels as measured inside the estuary close to the Carnsew sluice gate shown in blue on Figure 39 below, with the coastal model's predictions shown in red.

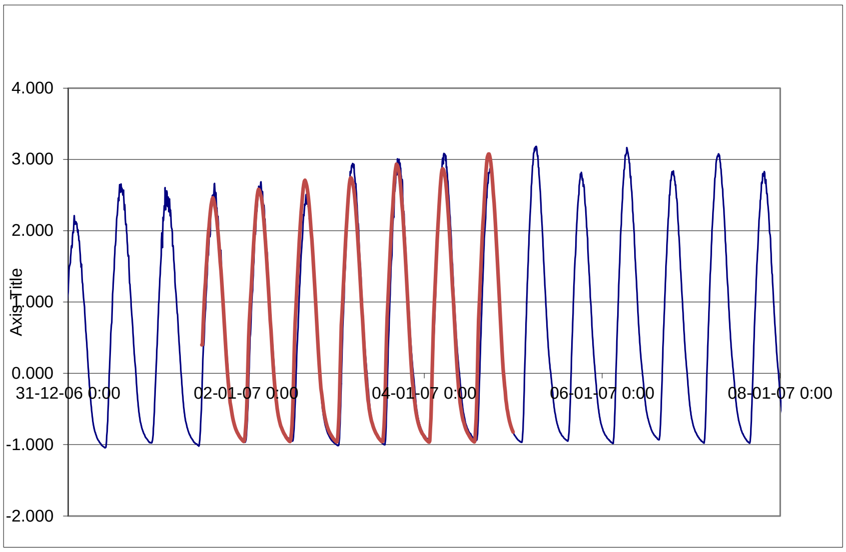

Figure 39: Coastal Model Calibration

Figure 39 shows good correlation between measured and modelled datasets, thus the model's high level outputs[25] may be used with a reasonable degree of confidence.

24 In 2D 'Depth Averaged' mode, the FLOW model assumes a standard vertical velocity profile; a 2D modelling approach was adopted; conversion to 3D mode would be straightforward, if required for more detailed analysis.

25 Calibration of the model for tidal stream velocities was not possible, due the absence of velocity. Velocity calibration would need to be carried out against ADCP data out in more detailed work.

9.1.2 Estuarine Oceanography Focus

An initial scenario was established, with Carnsew and Copperhouse Gates open, in order to establish a baseline against which to test flow speed variation. The model was run for a Spring tide, configured with the Carnsew and Copperhouse gates open. This showed that the model results were not, for current speeds in the navigation channel, particularly sensitive to the sluice dimensions, albeit this would need to be more closely examined in any further work.

Two variations were then examined, the first with a Carnsew turbine installation, the second with a Carnsew sluice operation, initiated at 3 Hours after High Water at Carnsew. The aim was to understand the impact on estuarine flow speeds of both the tidal range installation and the sluicing operation, and compare the two.

9.1.3 Sedimentary Transport

It is important to understand that the key mechanism that is leading to the silting of the Hayle Estuary is that the flood tide is dominant over the ebb tide:

> *'The dominance of the flood tide over Hayle Beach results in the transport of material towards the mouth of the estuary during a Spring tide, effectively squeezing the present deep-water navigation channel. The predominant wave approaches the coastline at Hayle Beach obliquely, facilitating the littoral drift of beach material towards the west and the estuary mouth.'*[26]

The important implication is that any reduction in the dominance of the flood-tide flow speeds may well reduce the silting of the estuary, in a way that improves the maintenance of the navigable channel. This mechanism may have as much if not more impact on the silting problem than changes in sedimentary transport as a result of changes in the ebb-tide flow current speeds in the channel, be it as a result of power generation or sluicing operations. The balance between these different mechanisms would need to be the subject of more detailed analysis.

The full coastal modelling outputs are at Annexe B, but the key findings are set out below. Figure 40 shows difference against the baseline scenario of a Carnsew turbine installation.

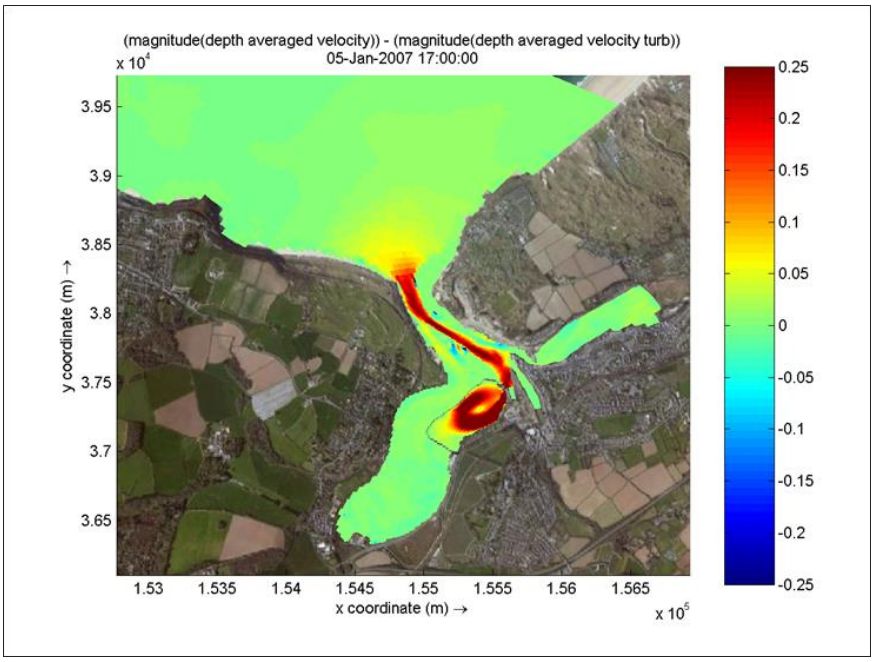

Figure 40: Carnsew Turbine Scenario – resulting flow speed *reduction* on flood-tide flow speeds

26 *Hayle Harbour Hydrodynamic Modelling Final Report – Revision R02*, dated 28 Nov 12, Babtie Group, Glasgow, p5.

Importantly, there is a reduction in the dominant flood-tide flow speeds, in the order of 0.20 ms^{-1} to 0.25ms^{-1}, as a result of the tidal range power generation operation.

For contrast, the impact of the sluicing model on ebb-tide flows through the channel, just after the sluice gates are open, is shown at Figure 41.

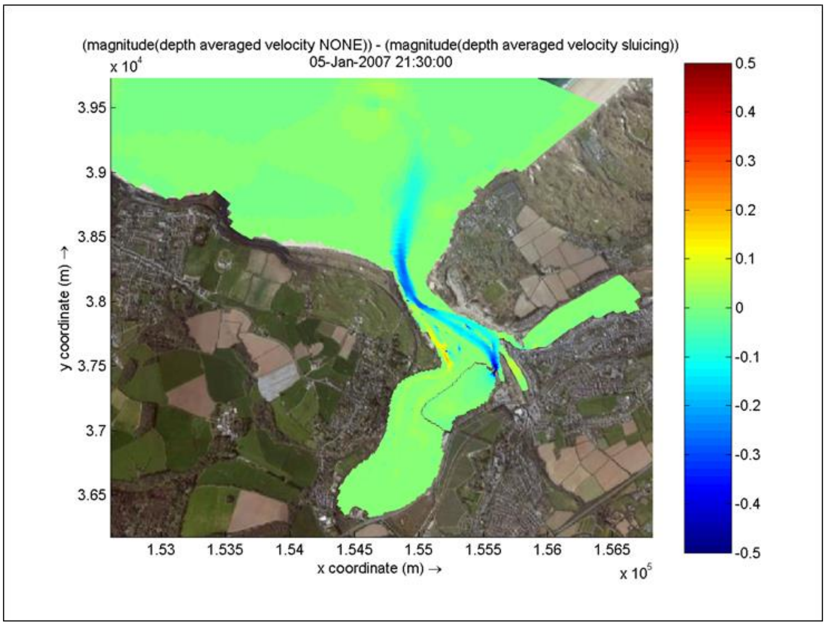

Figure 41: Carnsew Sluicing Scenario – resulting flow speed *increase* from ebb-tide sluicing operation at HW+3Hrs

This shows an increase in ebb-tide current speeds in the estuary of between 0.10 ms^{-1} to 0.20ms^{-1}, less than the impact of the tidal range power generation operation scheme on the dominant flood-tide flow speeds. The overall impact of the sluicing operation over the baseline scenario is shown at Figure 42 below.

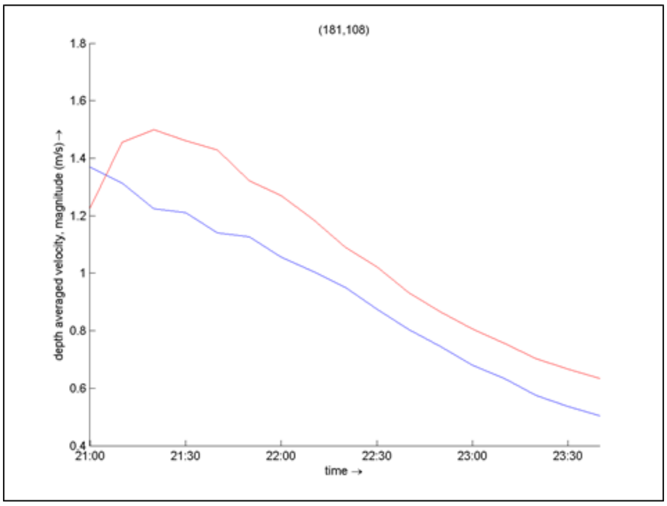

Figure 42: Carnsew Sluicing Operation Impact

This shows that the increase in flow speed in the channel as a result of the ebb-tide sluicing operation is just 0.10 ms^{-1} above the baseline flow, and delivered in a short pulse of around 45 minutes. Thereafter, the channel ebb-tide flow speeds reduce at the same rate as the baseline scenario.

From this it is possible to conclude that **were Carnsew power generation operations to take preference over ebb-tide sluicing, then the resulting reduction in the dominant flood-tide silting**

mechanism could compensate significantly for the loss of ebb-tide sluicing operation. This would, though, need to be investigated in detail, using a coupled yield and coastal model.

9.2 Environmental, Societal, and Economic Impacts

The impacts of the scheme(s), as viewed from oceanographic and technical perspectives, are set out below.

9.2.1 Environmental

Kaplan turbines are slow turning and the scheme(s) as envisaged will have sluicing penstocks, the latter allowing the safe migration of estuarine fish and molluscs. Thus whilst there will be site disruption, in the coffer-dammed area(s), during construction, once installed there should be little if any impact on marine flora and fauna through the operating life of the scheme(s). The annual loss of intertidal zone and, thus, wading bird habitats, will be low, but more detailed analysis would be needed to understand the impact over, say, a lunar month.

These impacts must be balanced against the environmental benefits of clean, predictable and local renewable energy, delivered from a project whose lifespan could extend well beyond the assumed 40 year assumed timescale: Rance Barrier continues in operation some 50 years since its construction, with no intention for decommissioning.

9.2.2 Societal

Setting aside the need for integration within a more comprehensive sluicing and flood protection operation, discussed in Section 8, it is difficult to see any significant societal disadvantages. Once constructed, the scheme(s) would entail little if any visual disruption nor to the leisure characteristics of both pools; and would also provide sufficient energy to power around 146 or so local households.

9.2.3 Economic

If the feasibility analysis' key findings that the scheme(s) are technically and economically feasible are substantiated in the more comprehensive analysis, then the economic benefits are likely to be wholly positive. Immediate local benefits would accrue as a result of CAPEX and OPEX expenditures in the local economy. More broadly, for: Hayle, the scheme(s) would provide a second marine renewable energy source alongside WaveHub and leverage the Hayle Marine Energy park; for Cornwall and the UK, the world's first tide-mill redevelopment could open up the possibility of securing a very significant technology and export opportunity.

Of particular export interest is that DFID have now begun investing, with InnovateUK, in UK renewable energy technology development for uses in developing countries. The mini and micro-tidal range approach set out above could have particular utility in Sub Saharan African countries with tidal energy opportunities, which are those adjoining the Mozambique Channel.

10 Conclusions & Recommendations

10.1 Conclusions

The key conclusions of this report are:

- Power Opportunity – theoretical levels of power available in Carnsew Pool is 1,911MWH per annum, and in Copperhouse Pool is 1,797MWH per annum. Carnsew Pool thus provides the best power opportunity. These power levels are akin to the installed capacity in micro-hydro (5KW to 100KW) and mini-hydro (100KW to 1MW) schemes;
- Mini & Micro Tidal Range Technologies – no technologies, on or close to market, are available at the right size or with the right operating modes to optimally extract this power; but there are no technical barriers to the development of such technologies. Such technologies would draw from both large scale *tidal range* schemes and *very low head* hydro river technologies;

- Technical Feasibility – there are practical and affordable civil engineering solutions to install mini and micro-tidal range turbines in 3 identified locations in the 2 pools. A modular installation process, using precast concrete modular installation pods, would be cost-effective and portable to other small tidal range schemes, in Cornwall, in the UK and internationally;
- Economic Feasibility – the analysis shows that the schemes would be economically feasible, with LCOEs potentially below £100MWH^{-1}, well below the Swansea Lagoon strike price bid of £168MWH^{-1}. A theoretical installation of 4 x 30KW bulb turbines would deliver annualised power of 474 MWH, with an LCOE of £98MWH^{-1}, sufficient to power around 146 homes. If the civil engineering costs can be reduced, then LCOE's of £86MWH^{-1} and below could be in achieved, albeit these figures are very sensitive to the civil engineering characteristics of particular *tidal range* installation sites;
- Site Selection – Carnsew Pool is the best of the two pools, but more analysis is needed to understand which of Carnsew Culverts or Carnsew Lock Gates represent the best installation and economic opportunity;
- Sluicing and Flood Protection – the impact of extracting tidal range energy upon existing sluicing plans may be less than intuitively anticipated. This is because of the positive impact of the scheme(s) on reducing flood-tide dominance and, thus, flood-tide sedimentary transport into the Hayle navigable channel, although this would need to be confirmed by more detailed 'coupled' analysis. In any event, it is judged that the scheme(s) would be best integrated into a more comprehensive Hayle operation, integrating *tidal range* energy, sluicing, and flood protection;
- Scheme Environmental, Societal and Economic Impacts – provided that the parallel requirements of channel sluicing and flood protection can be managed, there will be limited negative environmental impact, and a number of positive societal and economic impacts. For Hayle, the scheme(s) would provide a second marine renewable energy source alongside WaveHub and leverage the Hayle Marine Energy park; for Cornwall and the UK, the redevelopment of the world's first tide mills could secure a technology and export opportunity;
- Overall Feasibility – when viewed from a marine renewable energy perspective, and assuming that the right technologies can be developed at the right prices, then the scheme(s) are technically and economically viable, and worthy of comprehensive examination.

10.2 Recommendations

The key recommendations are:

- Technological R&D – public and private sector investment should be sought to investigate further the technical development of: coupled mathematical resource analysis and coastal models to allow sophisticated resource and impact analysis to be undertaken: turbine technologies required to deliver micro-tidal range and mini-tidal range power; modular civil engineering installation methodologies to minimise tidal range installations;
- Hayle Project – Carnsew Pool should be examined in detail to establish its investment appraisal potential as an early site for the installation of mini-tidal range and micro-tidal range technologies; the single turbine analysis shows that even a small scale demonstrator project could be economically attractive;
- South West Tide Mills Review – a local review should be undertaken to establish the power opportunity and civil engineering context of other historic tide mill sites in Cornwall and Devon, and the regional energy and economic opportunities therein.

<u>Annex A to Mojo's</u>

<u>MQ-6217-002-Rev-A</u>

<u>Dated 17 Aug 16</u>

A. References

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Annex B to Mojo's

MQ-6217-002-Rev-A

Dated 17 Aug 16

B. Coastal Modelling

Coastal Science Ltd, *A report for Mojo Maritime: Carnsew Pool Tide Mill: Preliminary 2D Hydrodynamic Modelling,* August 2016. Attached as separate pdf.

Annex C to Mojo's
MQ-6217-002-Rev-A
Dated 17 Aug 16

C. Acronyms

Acronym	Definition	Page
CAPEX	Capital Expenditure	11
CEP	Community Energy Plus	8
COTS	Commercial Off The Shelf	11
CSB	CSB Consilium Ltd	12
DFID	Department for International Development	6
FLOW	Delft3D-FLOW Coastal Modelling Software	39
LCOE	Levelised Cost of Energy	6
LIDAR	Light Detection And Ranging	5
MSL	Mean Sea Level	34
MWH	Mega Watt Hour	6
O&M	Operations & Maintenance	15
OPEX	Operational Expenditure	11
RSPB	Royal Society for Protection of Birds	12
UKHO	United Kingdom Hydrographic Office	38
WRAP	Waste and Resources Action Programme	8